NAVPERS 93400A-7

FUNDAMENTALS OF ELECTRONICS

VOLUME 7

ELECTROMAGNETIC CIRCUITS AND DEVICES

Bureau of Naval Personnel

PREFACE

This book is part of a nine-volume set entitled "Fundamentals of Electronics". The nine volumes include:

Volume 1a - NavPers 93400A-1a, Basic Electricity, Direct Current
Volume 1b - NavPers 93400A-1b, Basic Electricity, Alternating Current
Volume 2 - NavPers 93400A-2, Power Supplies and Amplifiers
Volume 3 - NavPers 93400A-3, Transmitter Circuit Applications
Volume 4 - NavPers 93400A-4, Receiver Circuit Applications
Volume 5 - NavPers 93400A-5, Oscilloscope Circuit Applications
Volume 6 - NavPers 93400A-6, Microwave Circuit Applications
Volume 7 - NavPers 93400A-7, Electromagnetic Circuits and Devices
Volume 8 - NavPers 93400A-8, Tables and Master Index

If you are becoming acquainted with electricity or electronics for the first time, study volumes one through seven in their numerical sequence. If you have a background equivalent to the information contained in volumes one and two, you are prepared to study the material contained in any of the remaining volumes. A master index for all volumes is included in volume eight. Volume eight also contains technical and mathematical tables that are useful in the study of the other volumes.

A question (or questions) follows each group of paragraphs. The questions are designed to determine if you understand the immediately preceding information. As you study, write out your answer to each question on a sheet of paper. If you have difficulty in phrasing an answer, restudy the applicable paragraphs. Do not advance to the next block of paragraphs until you are satisfied that you have written a correct answer.

When you have completed study of the text matter and written satisfactory answers to all questions on two facing pages of the book, compare your answers with those at the top of the next even-numbered page. If the answers match, you may continue your study with reasonable assurance that you have understood and can apply the material you have studied. Whenever your answers are incorrect, restudy the applicable material to determine why the book answer is correct and yours is not. If you make an honest effort to follow these instructions, you will have achieved the maximum learning benefits from each study assignment.

Follow the directions of your instructor in answering the review questions included at the end of each chapter.

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CHAPTER 56

ELECTRIC MOTORS

An electric motor is defined as a device which converts electrical energy into mechanical energy. Many of the everyday mechanical equipments contain some device which furnishes the mechanical force necessary for operation. Electric motors are used in communications and radar equipment to position and rotate large antennas.

56-1. Magnetic and Electromagnetic Principles

A discussion of the basic principles of operation of the ELECTRIC MOTOR involves a review of magnetism and electromagnetism.

The space surrounding a magnet where magnetic forces act is known as the magnetic field. This field is usually indicated by lines which are called flux lines or magnetic lines of force. These lines of force are assumed to leave the north pole of a magnet, pass through the surrounding space, and enter the south pole as shown in Figure 56-1. The lines of force then travel inside the magnet from the south pole to the north pole thereby completing a closed loop.

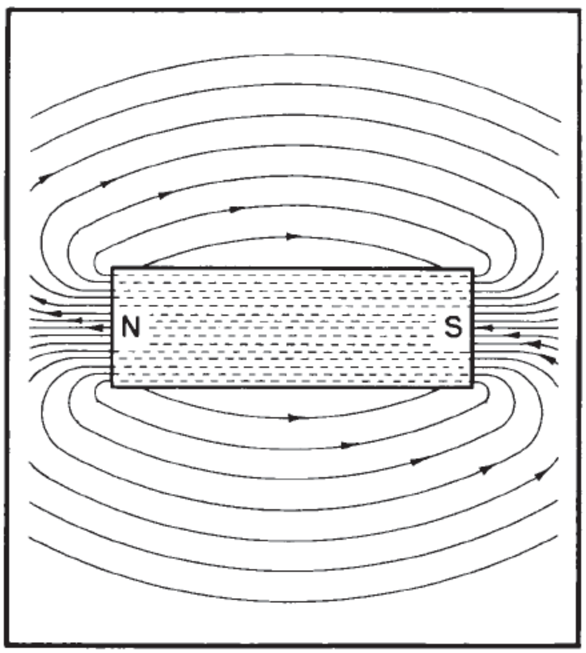

Figure 56-1 - Fields about a bar magnet.

There are several of the characteristics of these magnetic lines of force which must be mentioned. They are:

1. Magnetic lines of force are continuous and will always form closed loops.
2. Magnetic lines of force never cross.
3. Magnetic lines of force traveling in the same direction repel one another. Magnetic lines of force traveling in opposite directions tend to attract each other and combine.
4. Magnetic lines of force tend to shorten themselves. Therefore, the magnetic lines of force existing between two unlike poles cause the poles to be pulled together.
5. Magnetic lines of force pass through all known materials - magnetic or non-magnetic.

When a current is passed through a conductor, a magnetic field is formed around that conductor as shown in Figure 56-2. The direction of these lines of force may be determined by the left-hand rule. This rule is stated as follows:

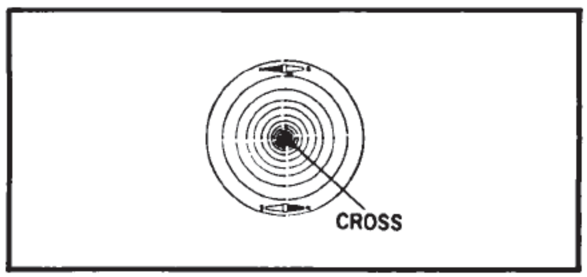

Figure 56-2 - Flux lines around a conductor.

"Grasp the conductor with the left hand so that the thumb points in the direction of current flow. The fingers will wrap around the conductor in the direction of the magnetic lines of force."

If the current carrying conductor is placed in a magnetic field as shown in Figure 56-3, motion of the conductor will be produced. The direction of motion may be determined by referring to the rules governing the action of lines of force. The rule of interest here states that magnetic lines traveling in the same direction repel one another, and lines of force traveling in opposite directions attract and

combine with one another.

Figure 56-3A shows the field about the conductor aiding the field at the bottom of the magnet and opposing the field at the top. This means that the conductor will be repelled from the bottom of the magnet and attracted toward the top. Figure 56-3B shows the current reversed through the conductor. This means that the fields will oppose at the bottom and aid at the top. This will result in a downward motion of the conductor. This is the underlying principle of motor action.

Perhaps the action of the basic motor can more easily be seen by using the diagram in Figure 56-4. Figure 56-4 shows a loop of wire suspended in a magnetic field. The loop of wire is also called an ARMATURE. The loop is connected to a COMMUTATOR-BRUSH assembly. The purpose of the commutator-brush assembly is to provide a contact area between the movable loop and the stationary dc source. Notice that one portion of the loop is connected to the commutator segment designated segment X, and the other portion of the loop is connected to the commutator segment designated segment Y. The commutator segments are insulated from one another. Segment Y is connected to brush A. Brush A, in turn, is connected to the negative terminal of the battery. Segment X is connected to brush B which is connected to the positive terminal of the battery. As the commutator segments turn, they will each be in contact with one of the brushes. Assume the starting position illustrated. Commutator segment Y is in contact with brush A, and the other segment, X, is in contact with brush B. When current is permitted to flow in the direction

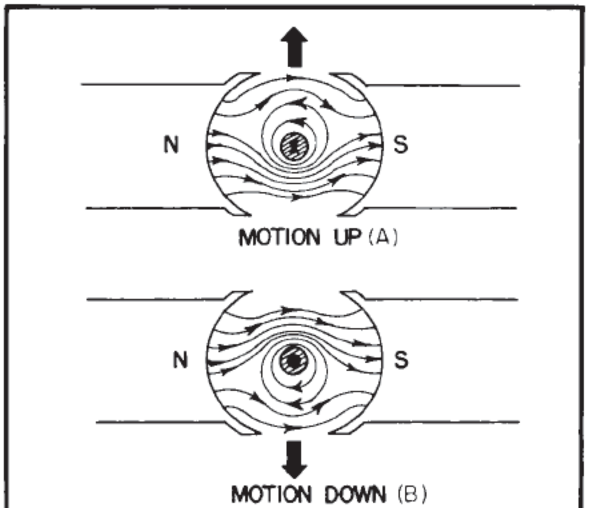

Figure 56-3 - Motion of a current carrying conductor in a magnetic field.

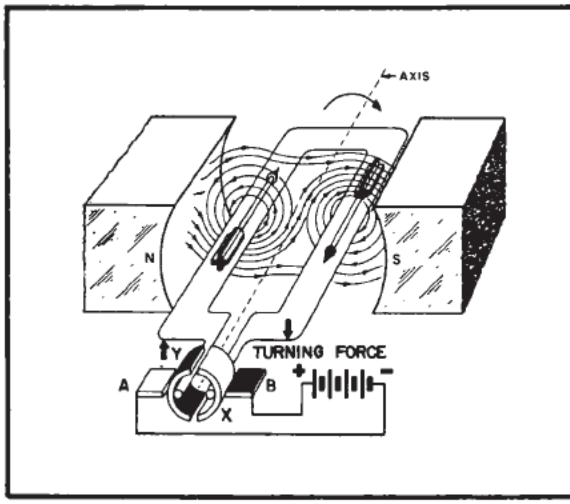

Figure 56-4 - Basic dc motor action.

indicated, fields are established about both sides of the loop of wire. The direction of current flow causes a magnetic field to exist in a direction which will cause the loop to start to rotate in a clockwise direction. In the left hand loop the fields are aiding and repelling at the bottom and opposing and attracting at the top. Therefore, the left hand loop will move in an upward and clockwise direction. The current flowing through the right hand portion of the loop causes an opposing and attracting field at the bottom resulting in a downward and clockwise motion. Therefore, the action of the left hand portion is aided by the action of the right hand loop. A shaft is mounted at the axis of the loop allowing the loop to rotate freely. Initially when the loop starts to rotate, it does so with a twisting force. This twisting force is known as TORQUE.

The torque will cause the conductors (loop) to rotate in the field. However, when the conductors reach a certain point in their travel (90° after the indicated starting position), they will be parallel to the lines of force established by the magnet. It would seem that at this position all motion would stop. This statement would be true if the conductors did not possess momentum. The actual condition is that the conductors possess sufficient momentum to ride past this point. Notice the position of both the loops and the commutators at this time (Figure 56-5). The loop is perpendicular to the lines of flux and the commutator bars are not making contact with the brushes. However, the momentum of the loop will be sufficient to cause the loop to pass through this point and reestablish contact with the commutator bars. Notice also that the commutator bars will now be connected to the opposite brushes, however, current flow will still be INTO brush A and OUT at brush B.

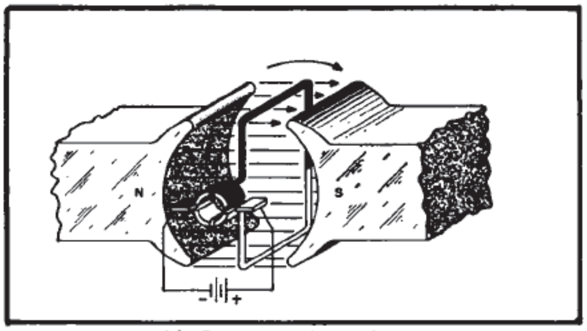

Figure 56-5 - Position of no apparent motion.

The direction of this current flow will establish fields that will continue the clockwise rotation. Figure 56-6 shows the loop moved to a position where it is again parallel to the field. The action will continue for the next 180° as it did for the first 180°. It is because of the switching action of the commutator that 360° of rotation of the armature can be achieved.

An armature composed of one loop of wire is used to explain the basic operation of a dc motor. A practical dc motor has many coils of wire in the armature winding. The armature has many slots into which are inserted many turns of wire as shown in Figure 56-7. This increases the number of armature conductors and thus produces a greater and more constant torque because the magnetic field is acting on a greater number of conductors at any given instant of time.

Q1. If a two loop dc motor is constructed, how many commutator bars does it contain?

56-2. Torque

The armature conductors for a motor are assembled in coils and connected to the commutator assembly. Current flows in one direction in the conductors under the north pole and in the opposite direction in the conductors under the south pole. To develop a continuous motor torque, the current in a coil must reverse when the coil passes the dead center position (top and

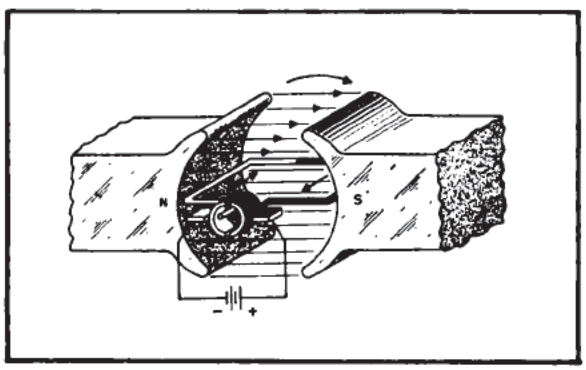

Figure 56-6 - 180° of rotation.

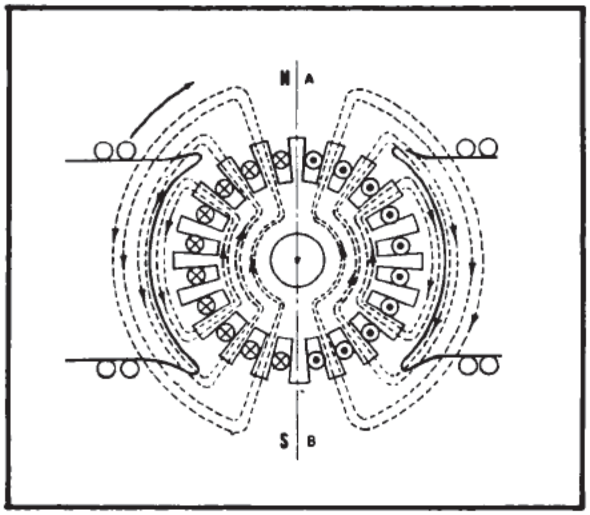

Figure 56-7 - Practical armature.

bottom). The function of the commutator is to reverse the current flow at the proper time to maintain current flow in all conductors under a given pole. The total torque is the arithmetic sum of the individual torques contributed by all the armature conductors.

When the speed of a motor is constant, the generated torque due to the armature current is just equal to the retarding torque caused by the combined effect of the friction losses in the motor and the mechanical load.

56-3. Counter EMF and Armature Reaction

In each motor, there is some generator action and in each generator there is some motor action. The generator action in a motor will now be considered. The right-hand rule for motors states: By extending the thumb, first and second fingers at right angles to each other, the first finger points in the direction of the south pole, the second finger in the direction of electron flow in a conductor, and the thumb will point in the direction of motion of the conductor with respect to the field. By applying this rule to the simple diagram in Figure 56-8, the direction of conductor motion can be determined. The motion, as shown, is upward. As the conductor is moved up through the field, it cuts lines of flux and has a voltage induced in it. Applying the left-hand generator rule, it is found that this generated voltage is in opposition to the impressed EMF. This counter voltage is induced in the windings of any rotating motor armature, and always opposes the impressed voltage. It is called the COUNTER ELECTROMOTIVE FORCE and is directly proportional to the speed of the armature and the strength of the flux. That is, the counter EMF is increased or decreased if the speed is in-

A1. Four, two for each loop.

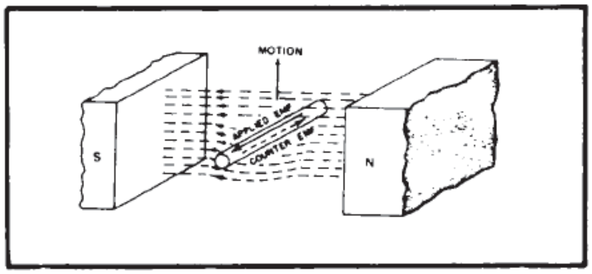

Figure 56-8 - Generator action in a motor.

creased or decreased respectively; the same is true if the field strength is increased or decreased.

The EFFECTIVE VOLTAGE (IR drop) in the armature is equal to the impressed voltage minus the counter EMF. The armature IR drop varies directly with the current flowing in the armature and with the resistance of the armature.

To produce an armature current, I_a, in an armature of resistance, R_a, requires an effective voltage of I_aR_a.

The current flowing through the armature can be found by the equation:

$$I_a = \frac{E_a - E_c}{R_a} \qquad (56\text{-}1)$$

where I_a is the current flowing through the armature, E_a the impressed (or applied) voltage across the armature, E_c the counter EMF and R_a the armature resistance. This equation can be transposed and written as:

$$E_c = E_a - I_aR_a \qquad (56\text{-}2)$$

In the case of the generator, the generated EMF is equal to the terminal voltage plus the armature resistance drop; and in the case of the motor, the generated or counter EMF is equal to the terminal voltage minus the voltage drop in the armature resistance. Expressing E_a in terms of E_c and I_aR_a,

$$E_a = E_c + I_aR_a \qquad (56\text{-}3)$$

In a motor, the main flux is always distorted in the opposite direction to the rotation as shown in Figure 56-9. Note that the resulting field in the motor shown in Figure 56-9 is strengthened at the leading pole tips and weakened at the trailing pole tips. This action causes the electrical neutral plane to be shifted back to A'B'. This is known as armature reaction. Thus, to

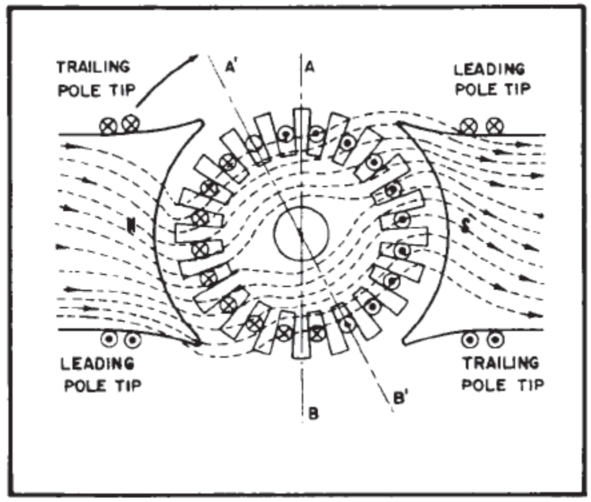

Figure 56-9 - Armature reaction in a motor.

obtain good commutation in a motor, it is necessary to shift the brushes from the mechanical neutral A-B in a direction opposite to that of the armature rotation.

The armature reaction is overcome in a motor by the use of extended pole tips, slotted pole pieces and compensating windings.

Q2. What is armature reaction?

When the mechanical load on the motor increases, armature reaction increases, and the electrical neutral plane is shifted further in the direction oppostie to that of the armature rotation. To maintain sparkless commutation, the plane of the brushes will have to be shifted to the newly established electrical neutral plane. When the load is reduced, the brushes are shifted in the opposite direction. Thus, for sparkless commutation, it is necessary to manually shift the brushes when the load varies.

Nearly all motors of more than one horsepower depend on COMMUTATING POLES, sometimes called INTERPOLES, rather than on the shifting of brushes to obtain sparkless commutation.

The interpole series field coil in a motor is connected to carry the armature current. As the load varies, the interpole flux varies, and the proper point of commutation is automatically fixed with load change. It is not necessary to shift the brushes when there is an increase or decrease in load. The brushes are located on the no-load neutral and remain in that position for all conditions of load. The effect of interpoles on armature counter EMF is shown in Figure 56-10.

The motor may be reversed by reversing the direction of the current in the armature. When

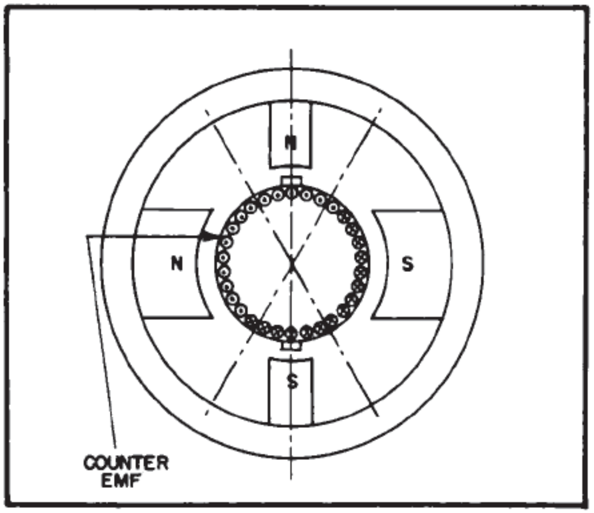

Figure 56-10 - Effect of interpoles on armature counter EMF.

the armature current is reversed, the current through the interpole is also reversed, and therefore the interpole still has the proper polarity to provide automatic positioning of the point of commutation.

Q3. What must be done to the brushes to maintain sparkless commutation?

56-4. Speed Regulation

SPEED REGULATION concerns the ability of a motor to maintain its speed when a load is applied. It is an inherent characteristic of a motor and remains the same as long as the applied voltage does not vary. The speed regulation of a motor is a comparison of its no-load speed to its full-load speed, and is expressed as a percentage of full-load speed. Thus:

Percent of regulation =

$$\frac{\text{no-load speed} - \text{full-load speed}}{\text{full-load speed}} \times 100 \quad (56\text{-}4)$$

For example, if the no-load speed of a shunt motor is 1600 rpm and the full-load speed is 1500 rpm, the speed regulation is:

$$\frac{1600 - 1500}{1500} \times 100 = 6.6\%$$

The lower the speed regulation percentage figure of a motor, the more constant the speed will be under varying load conditions, and the better will be the speed regulation. The higher the speed regulation percentage figure, the poorer is the speed regulation.

MOTOR CONNECTIONS

Practical dc motors do not use a permanent magnet to supply the necessary flux. Ordinarily, the flux is supplied by an electromagnet. When current is passed through a winding, poles are established at each end of the winding.

To change the direction of rotation of the electromagnetic type of dc motor involves reversing the direction of current through the field winding or the armature winding. The field coil or field winding is the winding in an electromagnetic dc motor which supplies the magnetic field. Since it is normally found in a stationary position it is called a STATOR WINDING. The armature winding is called the ROTOR WINDING. The relationship between the rotor and the stator winding is important because it will govern the characteristics of the machine. There are primarily two types of motor connections that will be of concern here. They are the SERIES MOTOR and the SHUNT MOTOR. The series motor is so designated because the field is connected in series with the rotor winding. The shunt type has the field coils connected in parallel with the armature (rotor) winding.

56-5. Shunt Motors

The field circuit of a shunt motor is connected across the line, and is thus in parallel with the armature as shown in Figure 56-11.

If the supply voltage is constant, the current through the field coils, and consequently the field flux, will be constant. When there is no load on the shunt motor, the only torque necessary is that required to overcome bearing friction and windage loss. The rotation of the armature coils through the field flux establishes a counter EMF that limits the armature current to the relatively small value required to establish the necessary torque to run the motor on no load.

Figure 56-12 shows the relationships between speed, counter EMF, torque and armature current. During the period between 0 and t_1 the motor operates under conditions of equilibrium.

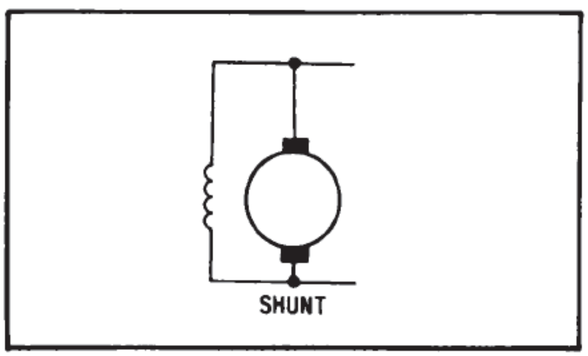

Figure 56-11 - Shunt motor.

A2. The tendency to shift the electrical neutral plane.

A3. They must be shifted to the electrical neutral plane.

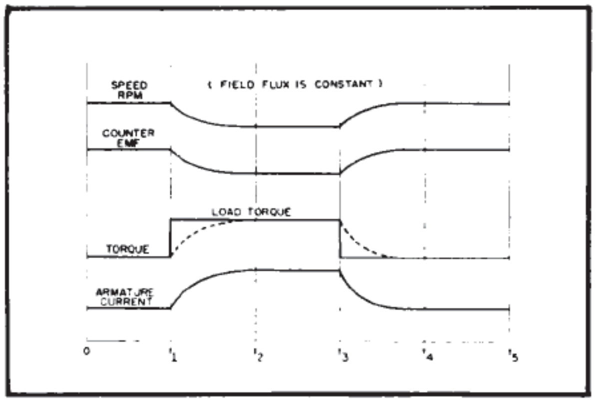

Figure 56-12 - Shunt motor load-speed-torque EMF relationships with respect to time.

When an external load is applied to the shunt motor, (t_1 to t_2), it tends to slow down slightly. The slight decrease in speed causes a corresponding decrease in counter EMF. Since the armature resistance is low, the resulting increase in armature current and torque is relatively large. Therefore, the torque is increased until it matches the mechanical opposition of the load. The speed of the motor then remains constant at the new value as long as the load is constant, (t_2 to t_3).

Conversely, if the load on the shunt motor is reduced, the motor tends to speed up slightly (t_3 to t_4). The increased speed causes a corresponding increase in counter EMF and a relatively large decrease in armature current and torque.

Thus, it may be seen that the amount of current flowing through the armature of a shunt motor depends upon the load on the motor. The larger the load, the larger the armature current; and conversely, the smaller the load, the smaller is the armature current. The change in speed causes a change in counter EMF and armature current in each case.

Q4. What is the advantage of the shunt wound motor?

56-6. Series Motors

The field coils of a series motor are connected in series with the armature as shown in Figure 56-13. With low flux density in the field iron, the series field strength is proportional to armature current.

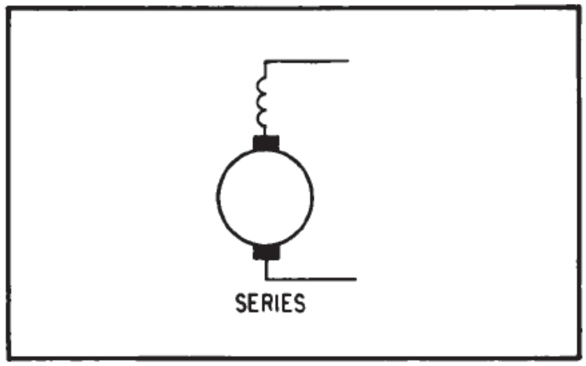

Figure 56-13 - Series motor.

If the supply voltage is constant, the armature current and the field flux will be constant only if the load is constant. If there were no load on the motor, the armature would speed up to such an extent that the windings might be thrown from the slots and the commutator destroyed by the excessive centrifugal forces. For this reason series motors are never belt-connected to their loads. The belt might break and the motor would then overspeed and destroy itself. Series motors are always connected to their loads directly, or through gears.

Figure 56-14 shows that, as the load increases, the armature speed slows down and the counter EMF is reduced. The current through the armature is increased and likewise the field strength is increased. This reduces the speed to a very low value. The armature current, however, is not excessive because the torque developed depends on BOTH the field flux and the armature current.

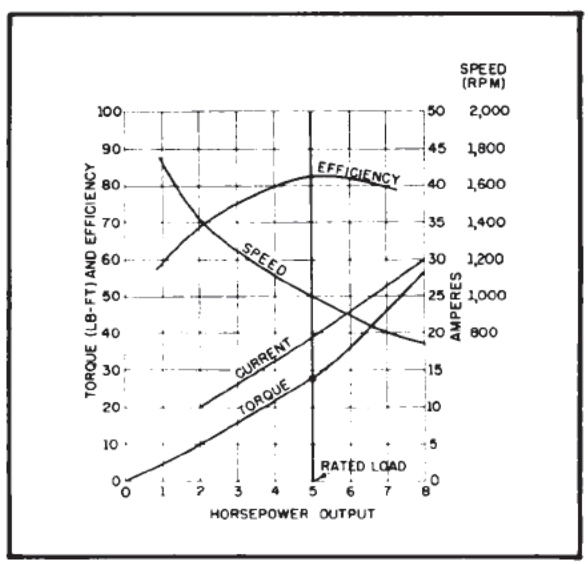

Figure 56-14 - Characteristic curves of a series motor.

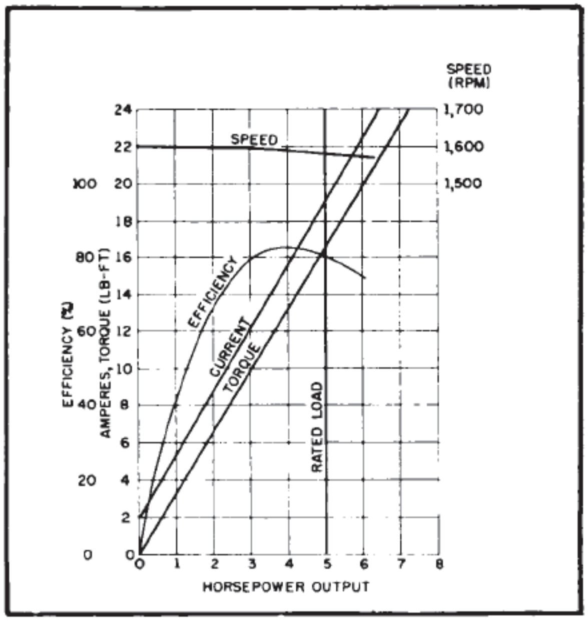

Figure 56-15 - Characteristic curves of a shunt motor.

Figure 56-15 shows that, when a heavy load is suddenly thrown on a shunt motor, it attempts to take on the load at only slightly reduced speed and counter EMF. The flux remains essentially constant and therefore, the increased torque is proportional to the increase in armature current. With heavy overload, the armature current becomes excessive and the temperature increases to a very high value. The shunt motor cannot slow down appreciably on heavy load, as can the series motor; hence the shunt motor is more susceptible to overload.

The series motor is therefore used where a wide variation in both torque and speed is desirable such as traction equipment, blower equipment, hoists, cranes, and so forth.

Q5. What is the advantage of the series motor as compared to the shunt motor?

56-7. Motor Efficiency and Speed Control

The efficiency of any type of machine is the ratio of the output power to the input power. This ratio is commonly expressed as a percent. Because all machines have some losses, the efficiency will never be 100 percent. Expressed as a percentage, efficiency becomes:

$$\text{efficiency} = \frac{\text{output}}{\text{input}} \times 100 \qquad (56\text{-}5)$$

There are various types of mechanical and electrical losses in motors. One loss is in BEARING FRICTION. This type of friction is reduced by proper oiling. Roller bearings have less friction loss than sleeve bearings. However, at excessive speed or under excessive load the loss due to bearing friction may be appreciable. A loss is also introduced by BRUSH FRICTION. This may be reduced by the use of a well-polished commutator and properly fitted brushes. WINDAGE LOSS is that loss due to the resistance of the air to a rapidly revolving armature. IRON LOSSES include eddy current loss and hysteresis loss in the aramture iron. COPPER LOSSES include the I^2R loss in the armature and field windings.

Speed control may be accomplished by means of a variable resistor in series with the armature. The rheostatic losses involved in this method of speed control are appreciable at low speeds, and the type of control undesirable if the motor is to be operated at greatly reduced speed for prolonged intervals.

A more economical method of speed control is by rheostatic adjustment of the field current. If the field strength is weakened, the speed of the motor is increased; and if the strength of the field is increased, the speed of the motor is decreased. This method finds practical application for use on the d-c shunt motor.

Figure 56-16 indicates a method of varying the strength of the field by means of a field rheostat. When the resistance of the field rheostat is increased, the field current is reduced and the field flux is reduced. This causes a reduction in counter EMF and a sharp increase in armature current, which causes an increase in armature speed. As the speed builds up, the counter EMF builds up, and the armature current is again reduced.

Q6. What are the losses that affect motor efficiency?

Work is accomplished when force acts through a distance. For example, when a force of one pound acts through a distance of one foot, one foot-pound of work has been accomplished. If 33,000 foot-pounds of work is done in one minute, one horsepower of work is accomplished.

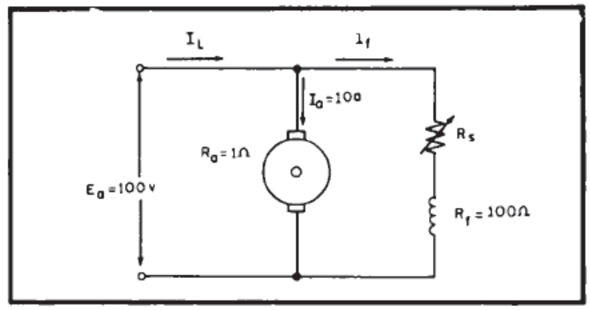

Figure 56-16 - Speed control by varying the strength of the field.

A4. Constant speed.

A5. The series motor is not as susceptible to overload.

A6. Bearing friction, brush friction, windage loss, iron loss, and copper loss.

Assume that an armature makes 100 revolutions per minute and that the effective radius of the armature is 1.59 feet. The circumference (the distance through which the force moves in one revolution of the armature) is:

$$C = 2\pi r$$

$$C = 2 \times 3.14 \times 1.59 = 10 \text{ feet}$$

Assuming that a total effective force of 200 pounds acts on the armature tangent to 10 foot circumference, the work done in one revolution is:

$$\text{work} = \text{force} \times \text{distance}$$

$$W = 200 \times 10 = 2,000 \text{ foot-pounds}$$

The work done in 100 revolutions would be 200,000 foot-pounds. The horsepower is therefore:

$$\text{h.p.} = \frac{\text{foot-pounds per minute}}{33,000}$$

$$\text{h.p.} = \frac{200,000}{33,000} = 6.06 \text{ horsepower}$$

The horespower developed by a motor armature may be derived from the general expression:

$$\text{h.p.} = \frac{FV}{33,000} \qquad (56\text{-}6)$$

where F is the total force in pounds tangent to the effective circumference of the armature, and V is the velocity of a point on this circumference in feet per minute. Velocity is determined as:

$$V = 2\pi r\, N \qquad (56\text{-}7)$$

where (r) is the effective radius of the armature in feet, and N is the armature speed in revolutions per minute. The effective circumference is equal to 2π r. Substituting equation (56-7) in equation (56-6):

$$\text{h.p.} = \frac{2\pi r\, N\, F}{33,000} \qquad (56\text{-}8)$$

The torque in pound-feet produced by the motor armature is:

$$T = r\, F \qquad (56\text{-}9)$$

Substituting equation (56-9) in equation 56-8 and dividing numerator and denominator by 2π.

$$\text{h.p.} = \frac{2\pi NT}{33,000} = \frac{NT}{5,252} \qquad (56\text{-}10)$$

Substituting the values N = 100 rpm and T = 1.59 x 200 = 318 pound-feet of the preceding example is equation (56-8), the result is:

$$\text{h.p.} = \frac{100 \times 318}{5,252}$$

$$\text{h.p.} = 6.06$$

Thus, the horsepower developed by a motor depends on its speed and torque. Large, slow speed motors develop a large torque; whereas, other much smaller motors of the same horsepower rating operate at reduced torque and increased speed.

56-8. Polyphase Motors

Because of the availability of alternating current, ac motors find more application than dc motors. Most of them eliminate the use of commutator segments and brushes. This also eliminates many problems of maintenance and wear. It also eliminates the problem of dangerous sparking.

AC motors are manufactured in many different shapes, sizes, and horsepower ratings for use in an even greater number of applications. They are designed for use with either polyphase or single-phase power supplies.

This section will deal with the operating principles of the most common of all motors, the induction motor.

The rotating field is set up by out-of-phase currents in the stator windings. Figure 56-17A illustrates the manner in which a rotating field is produced by stationary coils, or windings, when they are supplied by a three-phase current source. For purpose of explanation, rotation of the field is developed in the figure by "stopping" it at six selected positions, or instants. These instants are marked off at 60° intervals on the sine waves representing currents in the three phases A, B, and C.

At the instant 1 the current in phase B is maximum positive. (Assume plus 10 amperes in this example). Current is considered to be positive when it is flowing out from a motor terminal, and negative when it flows into a motor terminal. At the same time, current

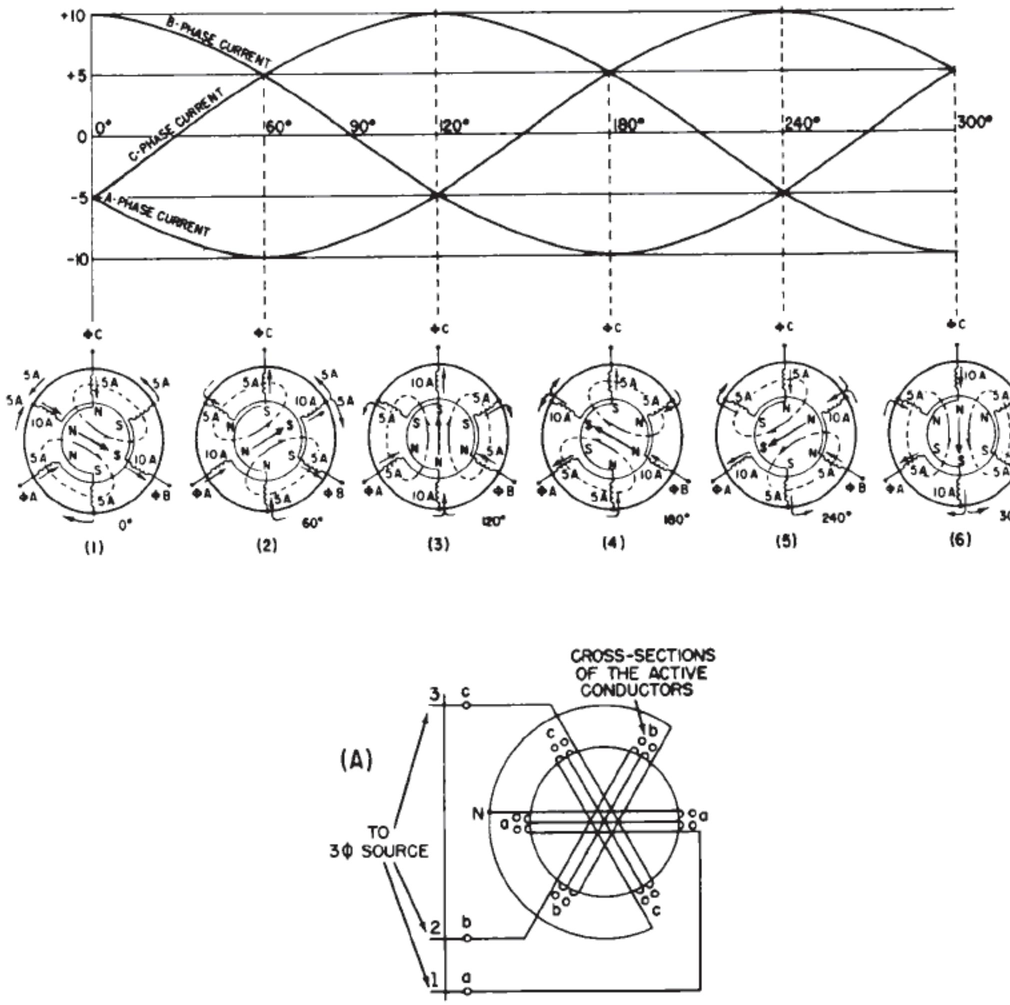

Figure 56-17 - Development of rotating field.

flows into the A and C terminals at half value (minus 5 amperes each in this case). These currents combine at the neutral (common connection) to supply plus 10 amperes out through the B phase.

The resulting field at instant 1 is established downward and to the right as shown by the arrow NS. The major portion of this field is produced by the B phase (full strength at this time) and is aided by the adjacent phases A and C (half strength). The field is a two-pole field extending across the space that would normally contain the rotor. This two pole field is the resultant of the vector sum of the individual stator fields.

At instant 2 the current in phase B is reduced to half value (plus 5 amperes in this example). The current in phase C has reversed its flow from minus 5 amperes to plus 5 amperes, and the current in phase A has increased from minus 5 to minus 10 amperes.

The resulting field at instant 2 is now established upward and to the right as shown by arrows NS. The major portion of the field is produced by phase A (full strength) and the weaker portions by phases B and C (half strength).

At instant 3 the current in phase C is plus 10 amperes and the field extends vertically upward; at instant 4 the current in phase B becomes minus 10 amperes and the field extends upward and to the left; at instant 5 the current in phase A becomes plus 10 amperes and the field extends vertically downward and to the left; at instant 6 the current in phase C is minus 10 amperes and the field extends vertically downward. Instant 7 (not shown) corresponds to instant 1 when the

field again extends downward and to the right.

Thus a full rotation of the two-pole has been accomplished through one full cycle of 360 electrical degrees of the three-phase currents flowing in the windings.

The direction of rotation of the magnetic revolving field may be changed by interchanging any two line leads to the three motor terminals. For example, in Figure 56-17B, if line 1 connects to phase A, line 2 to phase B, and line 3 to phase C, and the line currents reach their positive maximum values in the sequence 1, 2, 3, the phase sequence is a, b, c and the rotation is arbitrarily clockwise. If lines 1 and 2 are interchanged, the phase sequence becomes b, a, c, and the revolving field turns counterclockwise.

Most induction motors used by the Navy are designed to operate on single-phase power supplies, or the 3-phase supply used in the preceding discussion. When a single-phase supply is used, it is necessary to split the power supply into two separate coil groups. The required phase difference is then generally obtained by inserting capacitance in series with one of the groups.

In Figure 56-17 note that the sine waves of current traversed 300° through the six positions shown. Accordingly, the field rotated 300°. If the supplied current completes 60 cycles each second, the field would rotate at 60 revolutions per second (60 x 60 = 3,600 revolutions per minute). However, if the number of stator coils were doubled, producing a 4-pole field, the field will rotate only half as fast. Normally in an a-c induction motor, the magnetic field travels one rotation per pole pair, per winding, for each a-c cycle of applied emf. If the number of poles for each winding is doubled, the magnetic field has more pole pairs to travel and will take twice as long (two cycles of applied emf) to complete one rotation of all the pole pairs in one winding. Thus, it can be seen that the speed of the revolving field varies directly as the frequency of the applied voltage and inversely as the number of poles. Thus,

$$N = \frac{120f}{p} \qquad (56\text{-}11)$$

where N is the number of revolutions that the field makes per minute, f the frequency of the applied voltage in cycles per second, and P the number of poles produced by the 3-phase winding.

The speed at which an induction motor field rotates is referred to as its SYNCHRONOUS speed, because it is synchronized to the frequency of the power supply at all times. A motor having a 2-pole, 3-phase stator winding connected to a 60-cycle source has a synchronous speed (magnetic revolving field speed) of 3,600 rpm. A two-pole 25-cycle motor has a synchronous speed of 1,500 rpm. Increasing the number of poles lowers the speed. Thus, a 4-pole 25-cycle motor has a synchronous speed of 750 rpm. A 12-pole 60-cycle motor has a synchronous speed of 600 rpm. Increasing the frequency of the line supply increases the speed with which the field rotates. Thus, if the frequency is increased from 50 to 60 cycles, and the motor has 4 poles, the speed of the field is increased from 1,500 rpm to 1,800 rpm.

The speed of the rotating field is always independent of load changes on the motor, provided the line frequency is maintained constant.

The driving torque of both ac and dc motors is derived from the reaction of current-carrying conductors in a magnetic field. In the dc motor, the magnetic field is stationary and the armature with its current-carrying conductors, rotates. The current is supplied to the armature through a commutator and brushes.

In induction motors, the rotor currents are supplied by electromagnetic inductions. The magnetic field rotates continuously at constant speed regardless of the load on the motor. The stator winding corresponds to the armature winding of a dc motor or to the primary winding of a transformer. The rotor is not connected electrically to the power supply. The induction motor derives its name from the fact that mutual induction (transformer action) takes place between the stator and the rotor under operating conditions. The magnetic revolving field produced by the stator cuts across the rotor conductors, inducing a voltage in the conductors. This induced voltage causes rotor current to flow. Hence, motor torque is developed by the interaction of the rotor current and the magnetic revolving field.

Figure 56-18 shows the essential parts of both stator and rotor. The purpose of the iron rotor core is to reduce air gap reluctance and to concentrate the magnetic flux through the rotor conductors. Induced current flows in one direction in half of the rotor conductors, and in the opposite direction on the remainder. The shorting rings on the ends of the rotor complete the path for rotor current.

The STATOR of a polyphase induction motor consists of a laminated steel ring with slots on the inside circumference. Stator phase windings are symmetrically placed on the stator and may be either wye or delta connected.

There are two types of rotors—the CAGE ROTOR and the FORM-WOUND ROTOR. Both types have a laminated cylindrical core with parallel slots in the outside circumference to hold the windings in place. The cage rotor has an uninsulated bar winding; whereas the form wound has a two-layer distributed winding with preformed coils like those on a dc motor armature.

A cage rotor is shown in Figure 56-19A. The rotor bars are of copper, aluminum, of a suit-

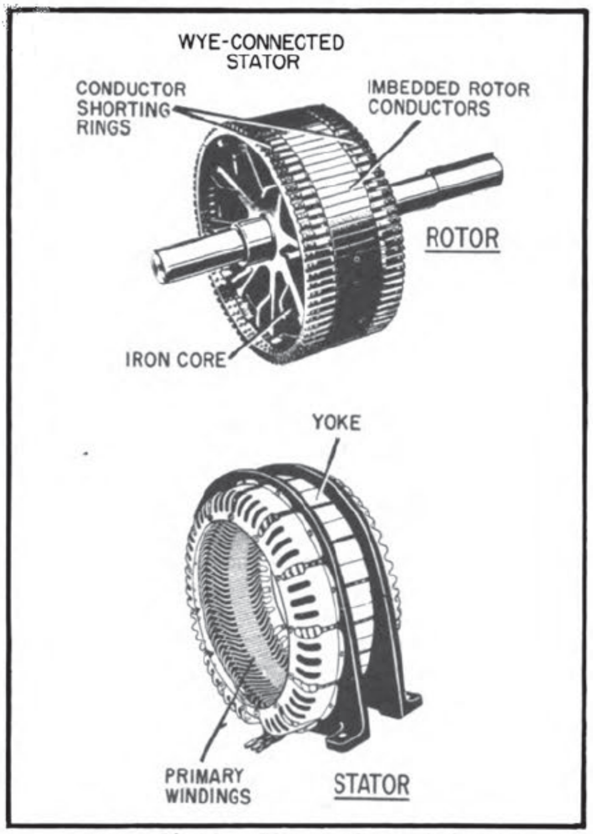

Figure 56-18 - Three phase induction motor.

able alloy placed in the slots of the rotor core. These bars are connected together at each end by rings of similar material. The conductor bars carry relatively large currents at low voltages. Hence, it is not necessary to insulate these bars from the core because the currents follow the path of least resistance and are confined to the cage winding.

A form-wound rotor, shown in Figure 56-19B, has a winding similar to a 3-phase stator windings. Rotor windings are usually wye connected with the free ends of the winding connected to three slip rings mounted on the rotor shaft. An external variable wye-connected resistance, shown in Figure 56-19C, is connected to the rotor circuit through the sliprings. The variable resistance provides a means of increasing the rotor-circuit resistance during the starting period to produce a high starting torque. The added resistance in the rotor circuit increases the rotor power factor, thereby providing additional rotor power. As the motor accelerates, the rheostat is cutout. When the motor reaches full speed, the sliprings are short-circuited and the operation is similar to that of the cage motor.

As previously described, the revolving field produced by the stator windings cuts the rotor

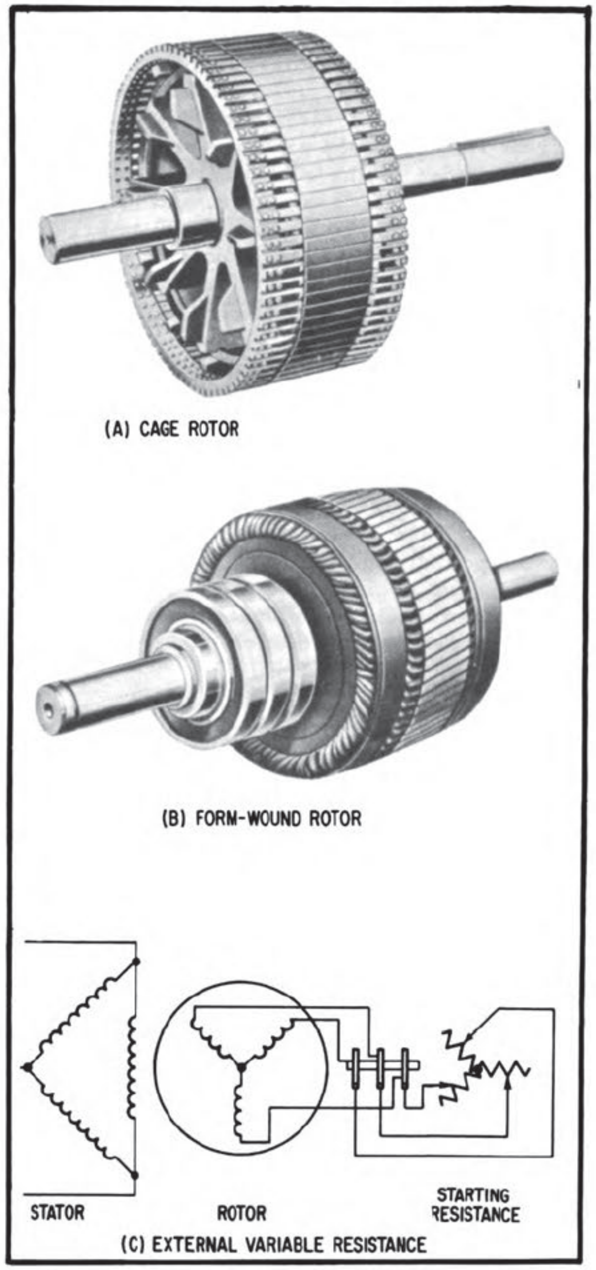

Figure 56-19 - Induction motor rotors.

conductors and induces voltages in the conductors. Rotor currents flow because the rotor end rings provide continuous metallic circuits. The resulting torque tends to turn the rotor in the direction of the rotating field. This torque is proportional to the rotor current, the field strength, and the rotor power factor.

As previously stated, a dc motor receives its armature current by means of conduction through the commutator and brushes; whereas, an induction motor receives its rotor current

by means of induction. In this respect the induction motor is like a transformer with a rotating secondary. The primary is the stator which produces the revolving field; the secondary is the rotor. At the start, the frequency of the rotor current is that of the primary stator winding. The reactance of the rotor is relatively large compared with its resistance, and the power factor is low and lagging by almost 90°. Because almost half of the conductors under the south pole carry current outward and the remainder of the conductors carry current inward, the net torque on the rotor as a result of the interaction between the rotor and the rotating field is small.

As the rotor comes up to speed in the same direction of the revolving field, the rate at which the revolving field cuts the rotor conductors is reduced and the rotor voltage and the frequency of rotor currents are correspondingly reduced. Hence, at almost synchronous speed the voltage induced in the rotor is very small.

Slip is the decimal equivalent of the difference between synchronous speed and rotor speed and is expressed mathematically.

$$S = \frac{N_s - N_r}{N_s} \qquad (56\text{-}12)$$

where N_s is the number of revolutions per minute of the stator field, and N_r the number of revolutions per minute of the rotor.

When the rotor is starting, the difference in speed between the rotor and the rotating field is maximum; hence, the rotor reactance is maximum.

Normal operation is between two extremes of rotor slip, that is, when the rotor is not turning at all or when it is turning almost at synchronous speed. The motor speed under normal load conditions is rarely more than 10 percent below synchronous speed. At the extreme of 100 percent slip, the rotor reactance is so high that the torque is low because of low power factor. At the other extreme of zero rotor slip, the torque is low because of low rotor current.

The speed, N, of the rotating field is called the SYNCHRONOUS SPEED of the motor. As previously stated, the torque on the rotor tends to turn the rotor in the same direction as the revolving field. If the motor is not driving a load, it will accelerate to nearly the same speed as the revolving field. During the starting period, the increase in rotor speed is accompanied by a decrease in induced rotor voltage because the relative motion between the rotating field and the rotor decreases. There would then be no induced EMF in the rotor, no rotor current, and thus no torque.

It is obvious that an induction motor cannot run at exactly synchronous speed. Instead, the rotor always runs just enough below synchronous speed at no load to establish sufficient rotor current to produce a torque equal to the resisting torque that is caused by the rotor losses.

As stated previously, the cage-rotor induction motor is comparable to a transformer with a rotating secondary. At no load, the magnetic revolving field produced by the primary stator winding cuts the turns of the stator winding. This action generates a counter EMF in the stator winding, which limits the line current to a small value. This no-load value is called EXCITING CURRENT. Its function is to maintain the revolving field. Because the circuit is highly inductive, the power factor of the motor with no load is very poor. It may be as much as 30 percent lagging. Because there is no drag on the rotor, it runs at almost synchronous speed and the rotor current is quite small. Hence, the reaction of the rotor magnetomotive force on the primary revolving field is small.

When a load is added to the motor, the rotor slows down slightly; but the rotating field continues at synchronous speed. Therefore, the rotor current and slip increases. The increase in the EMF opposes the primary field flux and lowers it slightly. The primary counter EMF therefore decreases slightly and primary current increases. The load component of primary current maintains the rotating field and prevents its further weakening because of the rotor current opposition. Because of the relatively low internal impedance of the motor windings, a small reduction in speed and counter EMF in the primary may be accompanied by large increases in motor current, torque, and power output. Thus, the cage-rotor motor has essentially constant speed variable-torque characteristics.

If the induction motor is stalled by an overload, the resulting increased rotor current lowers the primary counter EMF and causes excessive primary current. This excessive current may damage the motor winding. When the rotor of an induction motor is locked, the voltage applied to the primary winding should not exceed 50 percent of its rated voltage.

When the motor is operating at full load, the load component of stator current is more nearly in phase with the voltage across each stator phase because of the mechanical output (true power component) of the motor. The power factor is considerably improved over the no-load condition. **As the mechanical load brings the rotor speed down to 75% of synchronous speed, the rotor power factor angle approaches 45 degrees.**

At full load, however, the rotor reactance is much less than the motor resistance. When the motor is running, the rotor current is determined principally by the rotor resistance. The torque increases up to the pull-out point as

the slip increases. Beyond this point the torque decreases and the motor stalls. Because the change in speed from no load to full load is relatively small, the motor torque and the horsepower output are considered to be directly proportional.

The cage-rotor induction motor has a fixed rotor circuit. The resistance and inductance of the windings are determined when the motor is designed and cannot be changed after it is built. The standard cage-rotor motor is a general purpose motor.

If the load requires special operating characteristics, such as high starting torque, the cage rotor is designed to have high resistance. The starting current of a motor with a high resistance rotor is less than that of a motor with a low resistance rotor. The high resistance rotor motor has wider speed variations than the low resistance rotor motor. The high rotor resistance also increases the rotor copper losses, resulting in a lower efficiency than that of the low resistance type. These motors are used to drive cranes and elevators when high starting current is required and when it is desired to slow down the motor without drawing excessive currents.

The wound rotor, or slip ring, induction motor is used when it is necessary to vary the rotor resistance in order to limit the starting current or to vary the motor speed. Maximum torque at start can be obtained with a wound rotor motor with about 1.15 times full-load current; whereas, a cage-rotor motor may require 5 times full-load current to produce maximum torque at start. Because the rotor circuit copper losses are largely external to the rotor winding, the wound rotor motor is desirable for an application which requires frequent starts.

The advantages of the wound rotor induction motor over the cage rotor induction motor are: high starting torque with moderate starting current, smooth acceleration under heavy loads, no excessive heating during starting, good running characteristics, and adjustable speed. The chief disadvantage of the wound rotor is that the initial and maintenance costs are greater than those of the cage rotor motor.

Q7. Name two types of rotors.

56-9. AC Motor Starters

As in the case of dc motors, some type of starter (controller) may also be employed on ac motors to limit the initial inrush of current.

ACROSS-THE-LINE starters are the most common form aboard ship because of their simplicity and because ships are generally equipped with sufficient generating capacity to handle the high starting currents of the motors. This type of starter throws the stator windings of the motor directly across the main supply line. This may be feasible if the motor is not too large (5 horsepower or less) and if the generating capacity of the ac generator can take care of the added load.

PRIMARY RESISTOR starters insert a resistor in the primary circuit (the stator circuit) of the motor for starting, or for starting and speed control. This stator is used when it is necessary to limit the starting current of a large ac motor so as not to put too great a load on the system.

SECONDARY RESISTOR starters insert a resistor in the secondary circuit (the rotor circuit of the form-wound type of induction motor) for starting and speed control. This starter may be used to limit starting currents, but is usually found where speed control of a large ac motor is required. Examples are some elevators and hoists equipped with direct ac electric drives.

COMPENSATOR, or AUTOTRANSFORMER starters start the motor at reduced voltage through an autotransformer, and subsequently connect the motor to full voltage after acceleration. The autotransformer starter is the most common form of the reduced voltage type used for limiting the starting current of a motor.

REACTOR STARTERS insert a reactor in the primary circuit of an ac motor during starting, and subsequently short-circuit the reactor to apply full voltage to the motor.

A simplified schematic diagram of a compensator, or transformer, starter is shown in Figure 56-20. Assume that the line voltage is 100 volts and that when the taps on the autotransformer are positioned as shown (in the starting position) 40 volts will be applied to the 3-phase motor stator. With the reduction in motor voltage, there is a corresponding reduction in starting current drawn from the line. At the same time, the motor current supplied by the secondary low-voltage windings is proportionately increased by the transformer action.

After a proper time interval, during which acceleration occurs, full-line voltage is applied to the motor.

A resistance starter could be used in place of an autotransformer to lower the voltage applied to the stator. The power factor would be improved, but the line current would be greater. The autotransformer has the advantage in permitting the motor to draw a relatively large starting current from the secondary with a relatively low line current.

56-10. Single-Phase Motors

Single-phase motors, as their name implies, operate on a single-phase power supply. These motors are used extensively in fractional horsepower sizes in the Navy, commercial, and domestic applications. The advantages of using

A7. Wound rotor and cage rotor.

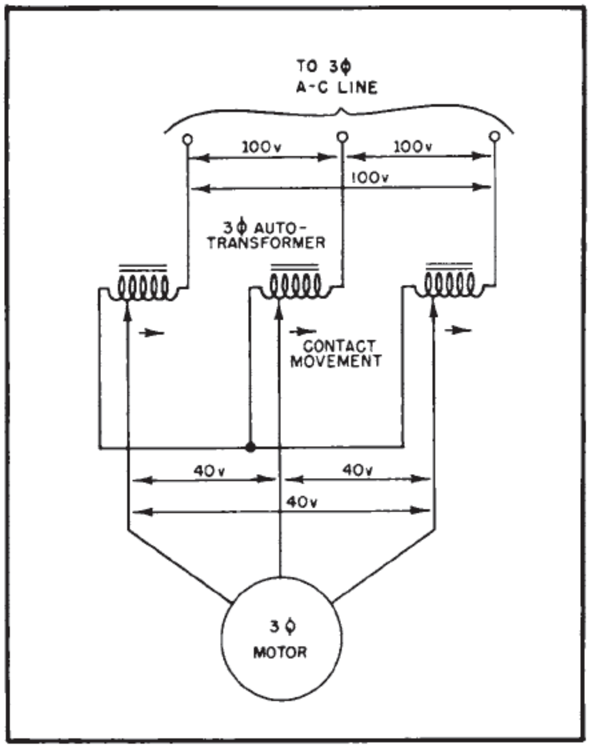

Figure 56-20 - Simplified schematic diagram of autotransformer starter.

single-phase motors, in small sizes, are that they are less expensive to manufacture than other types, and they eliminate the need for 3-phase ac lines. Single-phase motors are used in fans, refrigerators, drills, grinders, and so forth.

A single-phase induction motor with only one stator winding and a cage-rotor is like a 3-phase induction motor with a cage-rotor except that the single-phase motor has no magnetic revolving field at start and hence no starting torque. However, if the rotor is brought up to speed by external means, the induced currents in the rotor will cooperate with the stator currents to produce a relative motion, which causes the rotor to continue to run in the direction in which it was started.

Several methods are used to provide the single-phase induction motor with starting torque. These methods identify the motor as split-phase, capacitor, repulsion, and so forth.

Only the more commonly used types of single-phase motors are described. These include the split-phase motor, the capacitor motor, and the repulsion-start motor.

The split-phase motor shown in Figure 56-21A has a stator composed of slotted laminations that contain an auxiliary (starting) winding and a running (main) winding. The axes of these two windings are displaced by an angle of 90° (physical degrees). The starting winding has fewer turns and smaller wire than the running winding, hence has higher resistance and less reactance. The two windings are connected in parallel across the single-phase line supplying the motor. The motor derives its name from the action of the stator during the starting period. The single-phase is split into two windings which are displaced in space by 90°, and which contain currents displaced in time phase by an angle of approximately 15°. This is shown in Figure 56-21B. The current, I_s, in the starting winding lags the line voltage by about 30° and is less than the current in the main winding because of the higher impedance of the starting winding. The current, I_m, in the main winding lags the applied voltage by 45°.

At start, these two windings produce a magnetic revolving field that rotates around the stator gap at synchronous speed. As the rotating field moves around the air gap, it cuts across the rotor conductors and induces a voltage in them, which is maximum in the area of highest field intensity and therefore is inphase with the stator field. The rotor current lags the rotor voltage at start by an angle that approaches 90° because of the high rotor reactance. The interaction of the rotor currents and the stator field cause the rotor to accelerate in the direction in which the stator field is rotating. During acceleration, the rotor voltage, current, and reactance are reduced and the rotor currents come closer to an in-phase relation with the stator field.

When the rotor has come up to about 75 percent of synchronous speed, a centrifugally operated switch disconnects the starting winding from the line supply, and the motor continues to run on the main winding alone. Thereafter, the rotating field is maintained by the interaction of the rotor magnetomotive force (MMF) and the stator magnetomotive force.

This motor has the constant-speed variable torque characteristics of the shunt motor. Many of these motors are designed to operate on

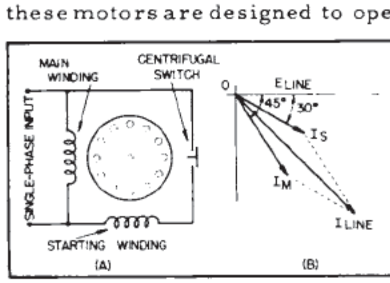

Figure 56-21 - Split-phase motor.

either 110 or 220 volts. For the lower voltage the stator coils are divided into two equal groups and these are connected in parallel. For the higher voltage the groups are connected in series. The starting torque is 150 to 200 percent of the full-load torque and the starting torque and the starting current is 6 to 8 times the full-load current. Fractional-horsepower split-phase motors are used in a variety of equipments such as washers, oil burners, and ventilating fans. The direction of rotation of the split-phase motor can be reversed by changing the leads.

The capacitor motor is a modified form of split-phase motor, having a capacitor in series with the starting winding. The capacitor produces a greater phase displacement of currents between the starting and running windings than is produced in the split-phase motor. The starting winding is made of many more turns of larger wire and is connected in series with the capacitor. The starting winding current is displaced approximately 90° from the running winding current. Since the axes of the two windings are also displaced by an angle of 90°, these conditions produce a higher starting torque than that of the split-phase motor. The starting torque of the capacitor motor may be as much as 350 percent of the full-load torque.

If the starting winding is cut out after the motor has increased in speed, the motor is called a CAPACITOR-START MOTOR. If the starting winding and capacitor are designed to be left in the circuit continuously, the motor is called a CAPACITOR MOTOR. They are used to drive grinders, drill presses, refrigerator compressors, and other loads that require relatively high starting torque. The direction of rotation of the capacitor motor may be reversed by interchanging the starting winding leads.

The repulsion-start motor has a form-wound rotor with commutator and brushes. The stator is laminated and contains a distributed single-phase winding. In its simplest form, the stator resembles that of the single-phase motor. In addition, the motor has a centrifugal device which removes the brushes from the commutator and places a short-circuiting ring around the commutator. This action occurs at about 75 percent of synchronous speed. Thereafter, the motor operates with the characteristics of the single-phase induction motor.

The starting torque of the repulsion-start induction motor is developed through the interaction of the rotor currents and the single-phase stator field. Unlike the split-phase motor, the stator field does not rotate at start, but alternates instead. The rotor currents are induced through transformer action.

In Figure 56-22, the brush axis is displaced from the stator polar axis by an angle of about 25°, and in this position maximum torque is developed.

The function of the commutator and brushes is to divide the rotor currents along an axis that is displaced from the axis of the stator field in the counterclockwise direction. The motor derives its name from the repulsion of like poles between the rotor and stator. Thus, the rotor currents establish the rotor poles N'-S', which are repelled by the stator poles N-S.

The starting torque is 250 to 450 percent of the full-load torque, and the starting current is 375 percent of the full-load current. This motor is made in fractional horsepower sizes and in larger sizes up to 15 horsepower, but has been replaced in large parts by the cheaper and more rugged capacitor motor. The repulsion-start motor has higher pull-out torque (torque at which the motor stalls) than the capacitor-start motor, but the capacitor-start motor can bring up to full speed loads that the repulsion motor can start but not accelerate.

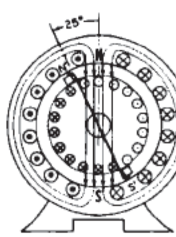

Figure 56-22 - Repulsion-start induction motor.

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If the rotor of an a-c motor is excited with a direct current supplied from an external source, through slip rings to the rotor windings, the rotor will effectively become a d-c electromagnet which will follow the rotating magnetic field with no slip. Since the rotor will rotate at synchronous speed, this type of motor is called a "synchronous motor".

EXERCISE 56

1. Describe the characteristics of magnetic lines of force.
2. What law of magnetic lines of force permits motor action?
3. Describe the construction of the basic dc motor.
4. Describe the action of commutation.
5. Describe the operation of the dc motor for at least 360° of rotation.
6. What is torque?
7. What are interpoles?
8. What causes the armature reaction in a dc motor?
9. Describe the advantages and disadvantages of the series and shunt dc motors.
10. How is the direction of rotation of a shunt dc motor reversed?
11. What is the main advantage of three-phase power as compared to single-phase power?
12. In a repulsion-start motor, why after the motor is started does it become an induction motor?
13. If the direction of rotation of a capacitor motor to be reversed, what can be done to accomplish this?
14. Upon disassembly of a motor, it is discovered that there are no brushes, commutator or slip rings. Two of the windings and a centrifugal switch are found in the field. What type of motor is it?
15. Describe the losses that influence motor efficiency.
16. Describe how a field may be caused to rotate.
17. Describe the types of ac motor starters.
18. Describe the operation of a single-phase motor.
19. What is the difference in the operation of the capacitor start motor and the repulsion start motor?
20. What are the advantages of the wound-rotor induction motor over the cage-rotor induction motor?

CHAPTER 57

SYNCHROS AND SERVO SYSTEMS

Synchros play a very important part in the operation of Navy electronic equipment. Nearly every type of radar equipment, sonar equipment, and fire control equipment contains a large number of synchros and servo mechanisms, which are vital to the operation of the equipment.

SYNCHRO ELEMENTS

57-1. Introduction to Synchros

SYNCHRO is a name given to a device which is used as a means of transmitting the angular position information of a rotary device (handwheel) to one or more remote indicators, such as radar antenna to radar repeater, handwheel to receiver indicator dials, etc.

In most cases, synchros are used where it would be impractical or quite involved to use the mechanical equivalent systems as shown in Figure 57-1A and B.

Synchro transmitters, receivers, control transformers, and differentials used in various systems are pictured in schematic symbols showing their external connections and relative positions of their windings. Figure 57-2A and B are generally used to show wiring connections. Figure 57-2C, D, and E are generally used for purposes of explaining the theory of operation of the synchro mechanisms.

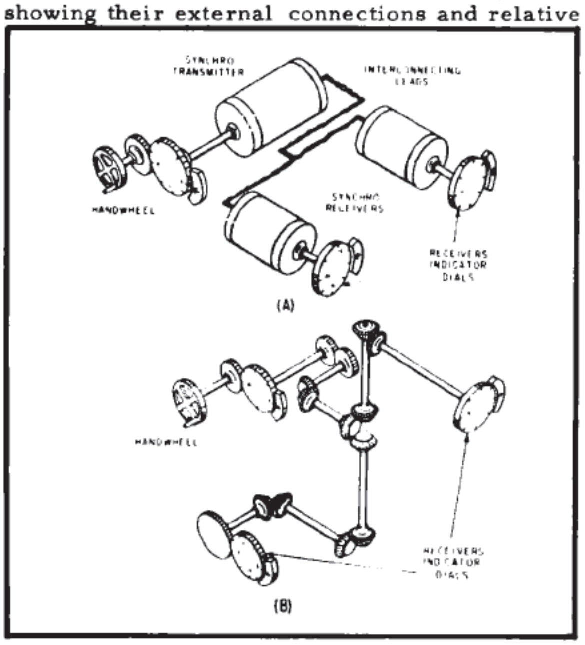


Figure 57-1 - Data transfer with synchros and data transfer with gears.

57-2. Construction

Synchros are electromagnetic devices which resemble ac electric motors. They are composed of a rotor and stators. The name rotor is given to the movable element of the device. It is similar to the armature in a motor. Stators are stationary windings mounted about, but not in contact with, the rotor winding at fixed intervals. The function of these elements will be explained later in this chapter.

The laminations of the rotor core are stacked together and rigidly mounted on a shaft. Slip rings are mounted on, but insulated from, the shaft. The ends of the coil are connected to these slip rings. Brushes riding on the slip rings provide continuous electrical contact during rotation, and low-friction ball bearings permit the shaft to turn easily.

There are two common types of synchro rotors now in use—the SALIENT-POLE, and the DRUM or WOUND rotor.

The salient pole rotor, which frequently is called a DUMB-BELL or BOBBIN because of the shape of its core laminations, is shown in Figure 57-3.

During one complete excitation cycle, the magnetic polarity of the rotor changes from

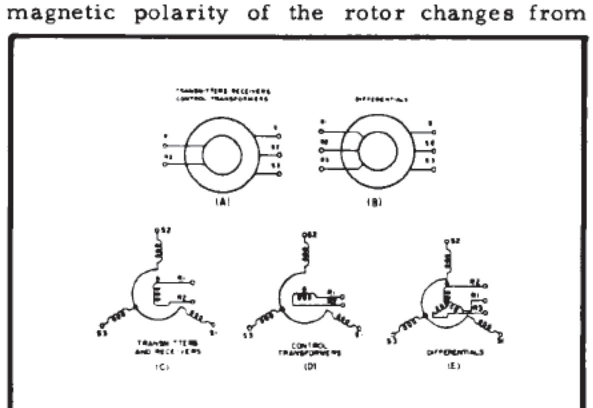


Figure 57-2 - External connections and relative positions of windings for Navy synchros.

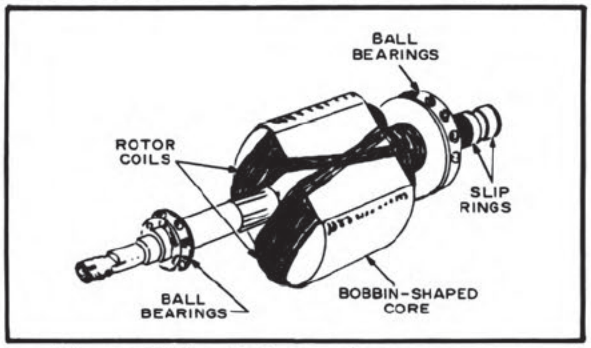


Figure 57-3 - Salient-pole rotor.

zero to maximum in one direction, to zero and reverses to maximum in the opposite direction, and returns to zero.

The drum or wound rotor is shown in Figure 57-4. This type of rotor is used in most synchro control transformers. The control transformer is the output of a synchro control system. The winding of the wound rotor may consist of three coils, so wound that their axes are displaced from each other by 120 degrees. One end of each coil terminates at one of three slip rings on the shaft, while the other ends are connected together. **The three winding rotor is found in such synchro units as the TDX, TDR, CDX, and CDR.**

The stator of a synchro is a cylindrical structure of slotted laminations on which three Y-connected coils are wound with their axes 120 degrees apart. Figure 57-5A shows a typical stator assembly and Figure 57-5B shows a stator lamination.

Stator windings are not connected directly to an ac source. Their excitation is supplied by the ac magnetic field of the rotor.

The rotor is mounted so that it may turn within the stator. A cylindrical frame houses the assembled synchro. Standard synchros have an insulated terminal block secured to one end of the housing at which the internal connections to the rotor and stator terminate, and to which external connections are made.

Q1. What is the main purpose of a basic synchro system?

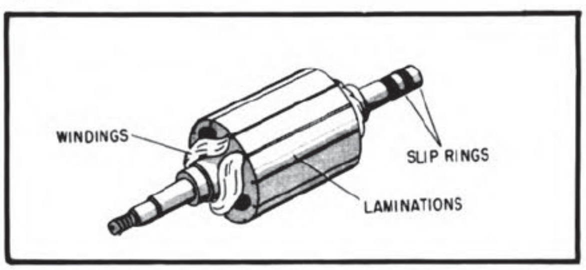


Figure 57-4 - Drum or wound rotor.

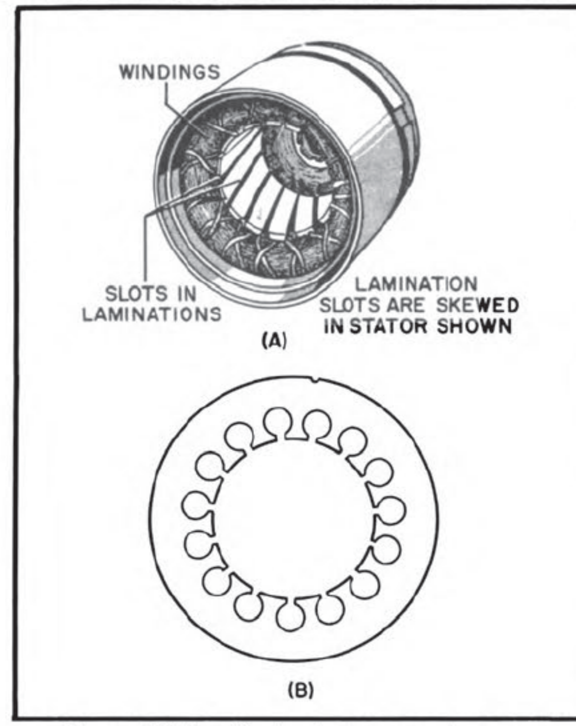


Figure 57-5 - Typical stator and stator lamination.

Q2. Describe the basic characteristics of the synchro rotor.

57-3. Functional Classification

Synchro systems consist of two or more inter-connected synchros. Units are grouped together according to their intended function. The seven common types, or functional classification, are defined briefly here. More complete descriptions are given in paragraphs to follow. Table 57-1 lists the input, output, and military abbreviations.

Torque transmitter (TX). A torque transmitter is a unit which electrically transmits angular information according to the physical position of its rotor with respect to its stator. The rotor position is determined mechanically by the information to be transmitted; the end result is the transformation of angular data into electrical values. Torque transmitters are normally connected to torque receivers, or torque differential transmitters; under certain conditions they may be used as control transmitters.

Control Transmitter (CX). Except for being connected only to control transformers or control differential transmitters, control transmitters perform the same function as torque transmitters.

Functional Classification	Military Abbreviations	Input	Output
Torque Transmitter	TX	Rotor positioned mechanically or manually by information to be transmitted.	Electrical output from stator identifying rotor position supplied to torque receiver, torque differential transmitter or torque differential receiver.
Control Transmitter	CX	Same as TX	Electrical output same as TX but supplied only to control transformer or control differential transmitter.
Torque Differential Transmitter	TDX	TX output applied to stator; The rotor is mechanically positioned according to the amount that the data from the TX is to be modified.	Electric output from rotor (representing angle equal to algebraic sum or difference or rotor position angle and angular data from TX) supplied to torque receivers, another TDX, or a torque differential receiver.
Control Differential Transmitter	CDX	Same as TDX but data usually supplied by CX.	Same as TDX but supplied only to control transformer or another CDX.
Torque Receiver	TR	Electrical angular position data from TX or TDX supplied to stator.	Rotor assumes position determined by electrical input supplied.
Torque Differential Receiver	TDR	Electrical data supplied from two TDX's, two TX's or one TX and one TDX (one connected to rotor, one to stator)	Rotor assumes position equal to algebraic sum or difference of two angular inputs.
Control Transformer	CT	Electrical data from CX or CDX applied to stator; rotor positioned mechanically or manually.	Electrical output from rotor (proportional to sine of the difference between rotor angular position and electrical input angle).

TABLE 57-1 - Synchro functional classifications.

Torque Differential Transmitter (TDX). A torque differential transmitter electrically transmits angular information equal to the algebraic sum or difference of the electrical input supplied to its stator, from a torque transmitter, and the angular position of its rotor with respect to its stator. The rotor is positioned to modify or correct the data from the torque transmitter by some desired amount. The electrical output of this unit will be applied to a torque receiver, another torque differential transmitter, or a torque differential receiver.

Control Differential Transmitter (CDX). This is functionally the same as the torque differential transmitter except that it is used in control rather than torque systems.

Torque Receiver (TR). A unit whose rotor assumed an angular position determined by the electrical input supplied to its stator from a torque transmitter or torque differential transmitter. For proper operation, the rotor must be connected in parallel with the rotor of the associated torque transmitter, and both synchros energized from the same power source.

Torque Differential Receiver (TDR). A unit whose rotor assumes a physical position determined by the algebraic sum or difference of the electrical inputs supplied from two torque transmitters, or one torque transmitter and one torque differential transmitter.

Control Transformer (CT). A unit which, when supplied with electrical information from a transmitter or differential transmitter, produces an electrical output proportional to the sine of the difference between the control transformer rotor angle and the angle represented by the electrical input.

Q3. What is the basic difference between a torque receiver and a torque differential receiver?

A1. The main purpose of a basic synchro system is to transmit position information.

A2. The rotor of a synchro is the salient-pole type, bobbin shaped, and contains a single winding.

A3. The rotor of a torque receiver assumes an angular position determined by the electrical input supplied by a transmitter; where as the torque differential receiver rotor assumes a physical position determined by the algebraic sum or difference between the electrical inputs supplied by two transmitters.

57-4. Data Transmission Speeds

The gyro-compass aboard most naval vessels is located below deck near the center of gravity. Gyro-compass information, showing the ship's course, must be transmitted to various compass repeaters. In 1-speed data transmission a synchro transmitter rotor is geared to the gyro-compass so that one revolution of the rotor corresponds to one revolution of the gyro-compass. Further, in 36-speed data transmission the transmitter rotor is geared to turn through 36 revolutions for one revolution of the gyro compass. Simply, the speed of data transmission is the number of times a synchro transmitter rotor must turn to transmit a full range of values. Units transmitting data at one speed are frequently called 1-speed synchros, a unit transmitting data at 36-speed would be a 36-speed synchro, and so forth.

57-5. System Speeds

It is quite common to transmit the same data at two different speeds. Referring again to the gyro-compass, own-ship's-course data is commonly transmitted at 1-speed and 36-speed. A system where data is transmitted at two different speeds is called a DUAL SPEED system. Usually the dual speed system will be referred to by the speeds involved, for example "1 and 36-speed system." It is obvious that if data can be transmitted at different speeds or if the same data is transferred at different speeds, there must be certain advantages and disadvantages to the various methods.

For quantities without definite reference values, such as increasing range or bearing, a single speed system may be made as accurate as desired. Greater accuracy is also possible by using higher speeds of data transmission, such as 36-speed; however, in such an arrangement the self-synchronous feature of the 1-speed system is lost. Suppose that while the primary power to the system is interrupted the transmitter rotor is turned; when power is again applied to the system the transmitter and receiver rotor shafts are in corresponding positions, but an indicator coupled to the receiver rotor shaft may not show the actual position of the device geared to the transmitter. The number of positions in which the transmitter and receiver rotor shafts can correspond is the same as the transmission speed. Thus, in 36-speed data transmission, we have one correct position and 35 incorrect positions.

For accurate transmission without loss of self-synchronous operation, a dual-speed system is used.

When an error difference in position of transmitter and control transformer rotors exceeds a certain value, the 1-speed synchro takes control and reduces the error to a small value. The 36-speed synchro then takes control and increases the accuracy.

57-6. Basic Unit Operation

Synchro units have been compared with electrical transformers, differing only from conventional transformers by having one winding which may be rotated through 360°. Since this is true, it follows that the magnetic field existing within the unit may also be rotated through 360°. If an iron bar or electromagnet is inserted in this field and pivoted so that it is free to turn, it will always tend to line up in the direction of the field. This is the basic principle underlying all synchro operation.

In Figure 57-6, a current is applied to an electromagnet and a bar magnet is pivoted in its field. In part A, the bar is in alignment with the field, since the tenacity of the magnetic lines of force cause the magnetic lines of force to take as short a route as possible. If the bar is rotated and held in a position as in part B, the flux path is distorted and the magnetic forces of attraction between the two unlike poles in close proximity tends to restore the alignment

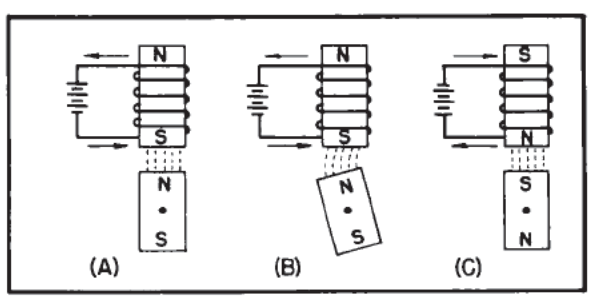


Figure 57-6 - Influence of electromagnet on a bar magnet rotor.

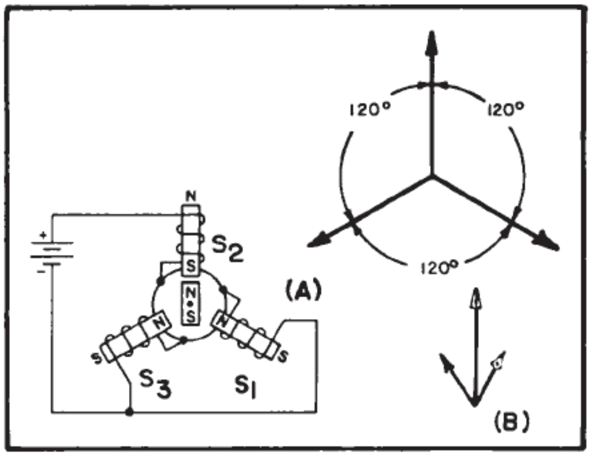


Figure 57-7 - Resultant field in dc system with stator coils spaced 120° apart.

between the two magnets and reduce the flux path to the minimum length. When released, the bar will snap back to the original position and remain in this alignment. Should the polarit of the electromagnet be reversed, as shown in part C, the field will reverse and the bar magnet will immediately displace 180° and take up an alignment opposite to the original position.

Figure 57-7A shows three coils wound on cores of magnetic material and secured in fixed positions 120° apart. One end of each coil is connected in common, while the other ends are connected to a battery with two of the coils in parallel and attached to one terminal of the battery and the remaining coil forms the return current path to the battery. The strongest field is set up by coil S_2, since the total current flows through it. Only one-half the total current flows through each of the coils S_1 and S_3, producing in each a field having one-half the strength of that of coil S_2. The resultant field is in the direction shown by the vector in part B, and tends to align the iron-bar rotor in the position indicated. By convention, this position is known as the zero-degree or ELECTRICAL ZERO position.

The stator-coil designations S_1, S_2 and S_3 are considered standard in synchro units. The S2 coil is represented schematically in the vertical position. This is shown in Figure 57-8.

A schematic sequence of battery connections and resultant 360° field rotation, in 60° steps, is illustrated in Figure 57-8.

When a source of 60 cycles alternating current is applied to a coil, as depicted in Figure 57-9, it is evident that the polarity of the electromagnet will reverse at the rate of 120 times a second.

In Figure 57-10, both stationary and rotating coils are excited by the same 60 cycle source. When the excitation is initially applied, the polarity established on the rotor ends will seek alignment with an unlike polarity existing on the fixed coil. As the polarity of the fixed coil reverses during each alternation of the source voltage, the polarity of the rotor ends will also reverse and the alignment of the rotor will not be disturbed.

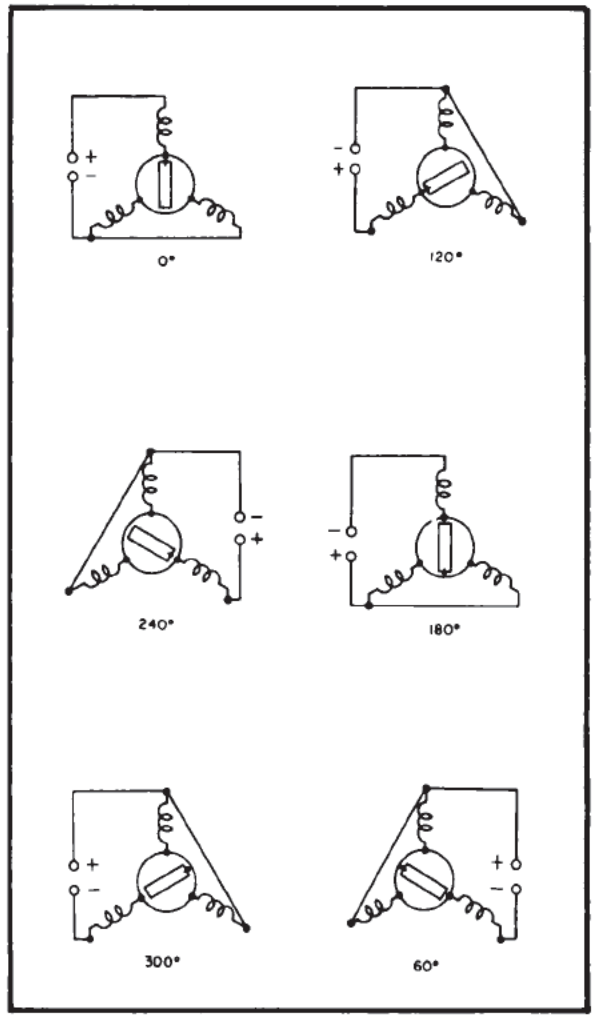


Figure 57-8 - Stator field rotations shown in 60° steps.

Before considering induced voltages in synchro units, it will be well to analyze the behavior of a simple transformer when one of its coils is rotated. Figure 57-11 represents a transformer having an equal number of turns in the primary and secondary windings.

For the sake of convenience, it will be assumed that no losses are encountered so that the secondary output voltage is the same as the applied primary voltage, or a ratio of one to one, when the primary and secondary windings

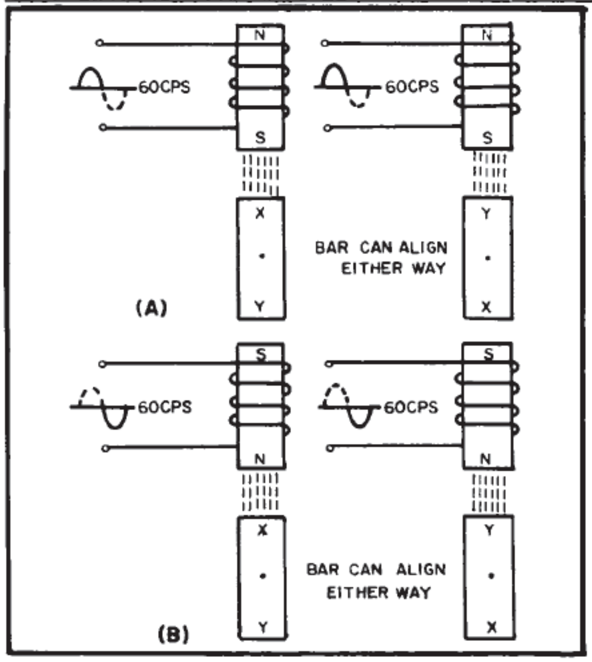


Figure 57-9 - Iron bar rotor ambiguity.

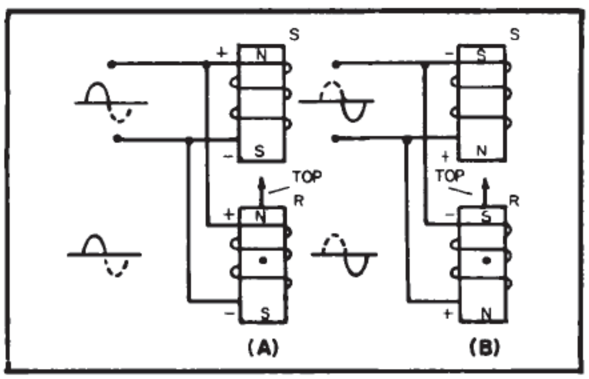


Figure 57-10 - Elimination of ambiguity by using electromagnet as rotor.

are parallel. At the 0° position, the flux linkage is maximum, the potential difference between S_1 and S_2 is shown to be 180° out-of-phase with the voltage applied between P_1 and P_2. Since the induced voltage will vary directly proportional to the cosine of the angular displacement between the windings, the secondary voltage will be 57.5 volts when the coil is rotated to an angle of 60° as shown in part C of the figure ($\cos 60^{\circ} \times E$ as $0^{\circ} = 0.5 \times 115 = 57.5$). Figure 57-11D shows the secondary coil at a right angle (90°) to the primary, and the output voltage is then zero. As the secondary is further rotated in the same direction, it will be noted that the output voltage rises again but that the polarity is reversed with respect to the primary voltage between P_1 and P_2. At the 180° position of rotation, the voltage between S_1 and S_2 is once again 115 volts, but the polarity is seen to be

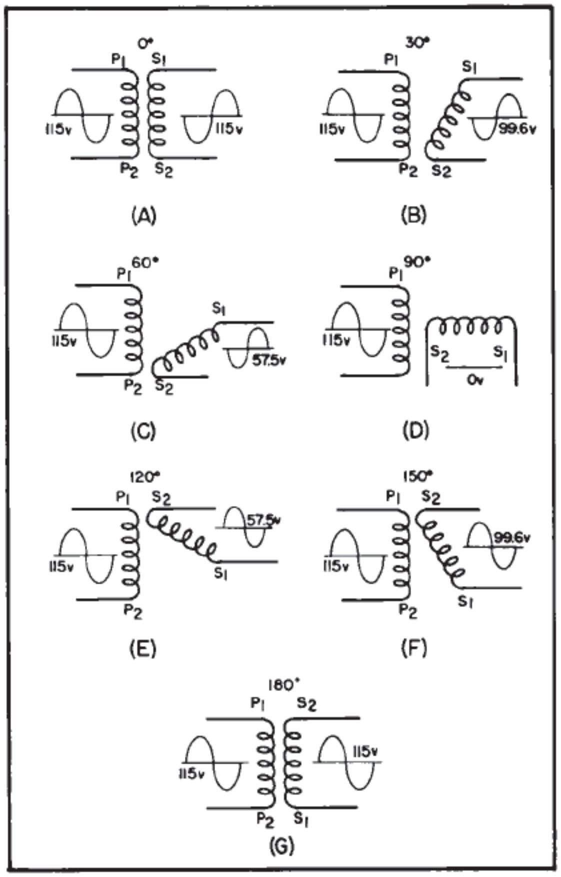


Figure 57-11 - Phase relationships between primary and secondary voltages.

in-phase with the applied voltage. If the rotation were continued through an additional 180°, the output voltage would again diminish to zero at the 270° position, experience a phase reversal, and build back up to the 115 volts value as the 0° position is reached.

Angular position of a synchro is the counterclockwise angular displacement of its rotor from the electrical zero position as viewed from the shaft extension end of the synchro.

Q4. How is the induced S voltage calculated?

Q5. With the rotor excited with 115 vac 60 cycle, turn the rotor 60 degrees clockwise from electrical zero and determine the following:

ES1 = ________ vrms
ES2 = ________ vrms
ES3 = ________ vrms
(Maximum voltage induced is 52 vrms)

Q6. Turn the rotor 33 degrees counterclockwise from electrical zero and determine the following:

ES1 = ________ vrms
ES2 = ________ vrms
ES3 = ________ vrms

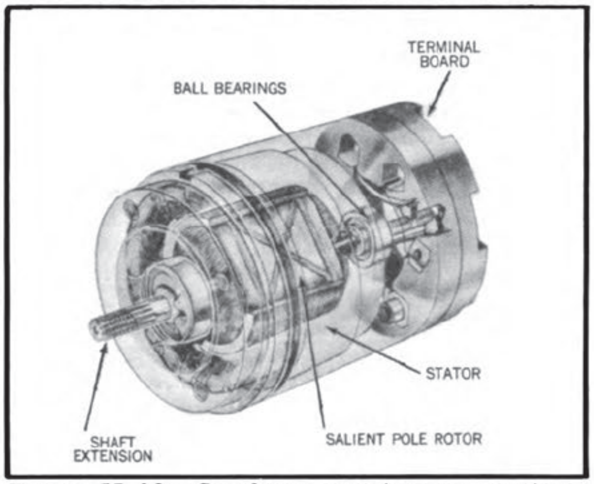


Figure 57-12 - Synchro transmitter or receiver; phantom view.

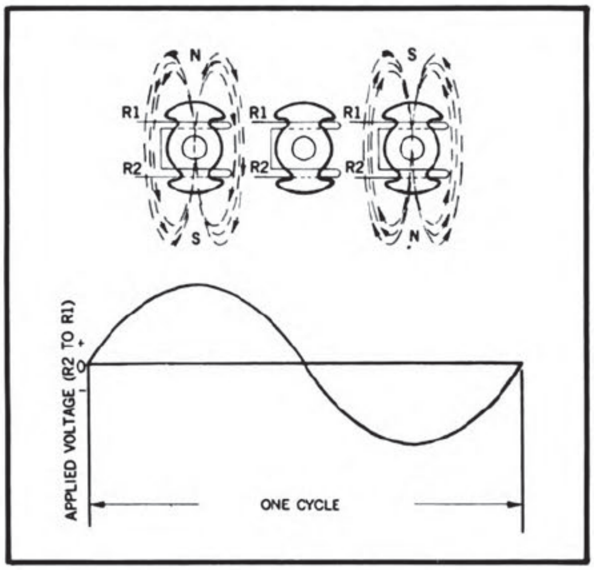


Figure 57-13 - Magnetic polarity variation in salient pole rotor.

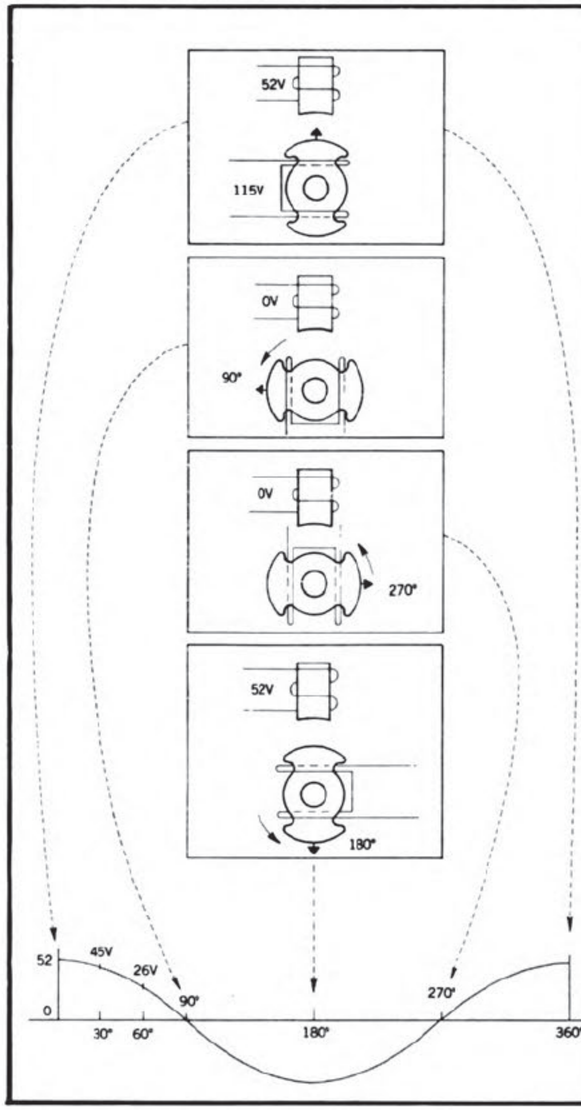


Figure 57-14 - Stator voltage versus rotor position.

57-7. Synchro Transmitter (TX)

The conventional synchro transmitter, shown in Figure 57-12, uses a salient pole rotor and a stator with skewed slots. When an ac excitation voltage is applied to the rotor, the resultant current produces a magnetic field as shown in Figure 57-13. The lines of force, or flux, vary continually in amplitude and direction and, by transformer action, induce voltages in the stator coils. The effective voltage induced in any stator coil depends upon the angular position of that coil's axis with respect to the rotor axis. When the maximum coil voltage is known, the voltage induced at any angular displacement can be determined. Figure 57-14 shows the voltages induced in one stator coil as the rotor is turned to different positions.

The turns ratio between the rotor and stator is such that when single-phase 115 volt excitation is applied to the rotor, the highest value of effective voltage that will be induced in any one stator coil will be 52 volts.

Because the common connection between the stator coils is not accessible, it is possible to measure only the terminal-to-terminal effective voltage; the terminal-to-terminal effective voltage for any rotor displacement can be determined. Figure 57-15 shows how these voltages vary as the rotor is turned. Values are shown above the line when the terminal-to-terminal voltage is in phase with the R_1 to R_2 voltage and below the line when the voltage is

A4. The voltage induced into a stator winding is equal to the maximum possible stator voltage times the cosine of the angular displacement between the windings.

A5. ES1 = 26 vrms
ES2 = 26 vrms
ES3 = 52 vrms

A6. ES1 = 43.7 vrms
ES2 = 2.7 vrms
ES3 = 46.3 vrms

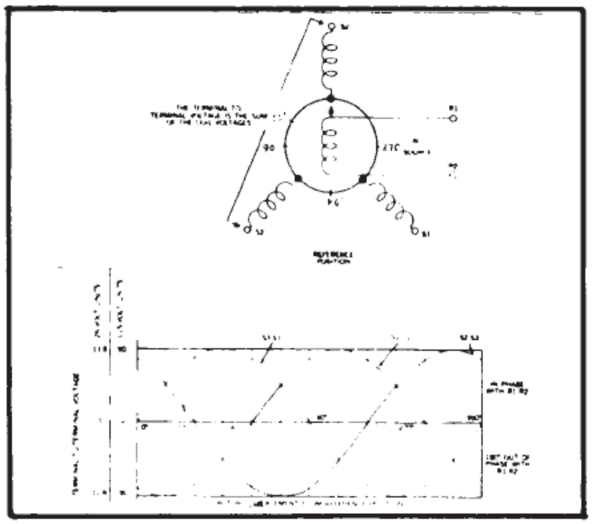


Figure 57-15 - Terminal-to-terminal voltages.

180° out-of-phase with the R_1 to R_2 voltage. Thus, negative values indicated a phase reversal. As an example, when the rotor is turned 50 degrees from the reference (zero degree) position, the S_3 to S_1 voltage will be about 70 volts and in phase with the R_1 to R_2 voltage, the S_2 to S_3 voltage will be about 85 volts, 180 degrees out of phase with the R_1 to R_2 voltage. Although the curves of Figure 57-15 resemble time-graphs of ac voltages, they show only the variations in effective voltage amplitude and phase as a function of the mechanical rotor position.

It is important to note that the synchro is NOT a three-phase instrument. In a three-phase machine, there are three voltages EQUAL in magnitude, each displaced from the others by 120 electrical degrees. In the synchro, a single-phase instrument, the three stator voltages VARY in magnitude, and one stator coil voltage is either in-phase or 180° out-of-phase, with another coil voltage.

57-8. Synchro Receiver (TR)

Torque receivers, usually called receivers, are electrically identical to torque transmitters of the same size. In some sizes of 400-cycle standard synchros, units are designated as torque receivers, but may be used as either transmitters or receivers.

Normally the receiver rotor is unrestrained except for brush and bearing friction. When power is first applied to a system, or when a receiver is switched into the system, the receiver rotor turns to correspond to the position of the transmitter rotor. This sudden motion can cause the rotor to oscillate, swing back and forth, around the synchronous position. Also due to the similarity between synchros and single-phase induction motors, the rotor may spin if turned fast enough. A mechanical device known as an INERTIA DAMPER can be used to prevent excessive oscillations or spinning of the rotor. Several variations of the inertia damper are in use. One of the more common types consist of a heavy brass flywheel which is free to rotate around a bushing which is attached to the rotor shaft. A tension spring on the bushing rubs against the flywheel so that they turn together during normal operation; if the rotor shaft turns or tends to change its speed or direction of rotation suddently, the inertia of the damper opposes the changing condition.

A synchro receiver is electrically connected to a synchro transmitter and is dependent upon the transmitter for angular position data. Its operation can be understood by noting that the current through each receiver stator winding is proportional to the voltage induced in the corresponding transmitter stator winding. The three receiver stator windings produce magnetic fields which, when added, result in a combined field the orientation of which is the same as that of the rotor field in the transmitter; that is, the direction of the combined fields, relative to the receiver stator structure, is the same as that of the transmitter rotor field relative to the transmitter stator structure. Operation may be considered as interaction between the receiver rotor and a magnetic field equivalent to that of the transmitter rotor. Since the receiver rotor acts like a magnet the poles of which are reversed with each reversal of the ac excitation. It lines up with the equivalent field, which also reverses with each reversal or the ac excitation.

Q7. What is the basic difference between the synchro transmitter and synchro receiver?

57-9. Basic System Operation

Synchros are seldom used singly. They work in teams and, when two or more synchros are interconnected to work together, they form a synchro system. Such a system may, depending on the types and arrangement of its components, be put to uses which vary from positioning a

sensitive indicator to controlling the motors which move equipment weighting many tons.

In many cases, the same system is called upon to perform both torque and control functions. The simplest synchro system consists of one torque transmitter and one torque receiver connected in parallel as shown in Figure 57-16.

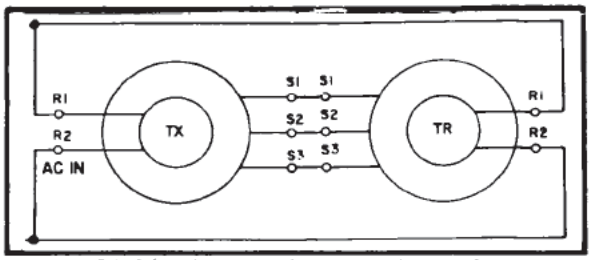


Figure 57-16 - External connections of a transmitter-receiver system.

It should be emphasized that the chief difference between the transmitter and the receiver is one of function. The transmitter is the unit whose shaft is turned; the receiver is the unit whose shaft follows. The two are not always interchangeable. They are electrically identical, but the receiver usually has an inertia damper and certain other refinements not present in the transmitter. In the following examples, forces equal and opposite to those turning the receiver rotor are present in the transmitter but do not affect its rotor position because the rotor is not free to turn. In practice, the transmitter rotor is mechanically connected, usually by gears, to the mechanism furnishing the information to be transmitted.

The outstanding characteristic of the transmitter-receiver system is that, as soon as both rotors are connected in parallel to the same ac source, the receiver rotor assumes and holds the same electrical position as the transmitter rotor does. Since the receiver is electrically identical to the transmitter and the two are connected in parallel, the voltage induced in each receiver stator coil exactly equals and opposes the voltage induced in the corresponding transmitter stator coil. Therefore, no current flows in the stator coils to establish a magnetic field. With no magnetic field, no torque is exerted on the rotor.

The fact that the rotors in the example in figure 57-23 are at zero is not important. Similar static conditions result from any angular position as long as it is the same angular position for both rotors. Unless the transmitters and receivers are energized from the same ac source, the system cannot function properly. If the latter is positioned at 0°, the receiver rotor turns to and remains at 0°. If the transmitter is turned to 30°, the receiver turns with it to 30°.

In accordance with Lenz's law, the field that is set up by the transmitter rotor coil induces voltages into the stator coils of such polarity that the combined stator field, produced if current is permitted to flow, will oppose the rotor field which induced it.

It is generally conceded that the most important factor to be considered in analyzing synchro operation is the RESULTANT FIELD. It has been shown that each stator coil produces a field of its own, the magnitude of which is proportional to the voltage induced in it. However, the fields from all three stator coils combine to form a resultant field, and this field is the basis of synchro operation. The magnitude of the resultant field remains constant. To determine the DIRECTION of the resultant field, the following rules are helpful:

RULES FOR SYNCHRO TRANSMITTERS AND RECEIVERS

1. In a synchro transmitter, the field of any stator coil will always oppose the field of the rotor coil.
2. The resultant field in the transmitter stator will always oppose the transmitter rotor field.
3. The resultant field in the receiver stator, since the coils are in series with the transmitter stator coils, will be in a direction to the resultant stator field in the transmitter (same direction as the transmitter rotor field).
4. The receiver rotor field will tend to align in the same direction as the resultant receiver stator field.
5. When transmitter and receiver rotor coils are in correspondence, the rotor coils induce equal and opposite voltages in their respective stator coils, causing the resultstator fields to cancel. Thus, stator current is reduced to zero.

Figure 57-17 shows the internal connections and physical relationships of the stators of a basic synchro system consisting of a single torque transmitter and one torque receiver. The rotor of the transmitter is shown in its proper perspective; however, the receiver rotor is omitted since the effects of an energized rotor will not be considered initially.

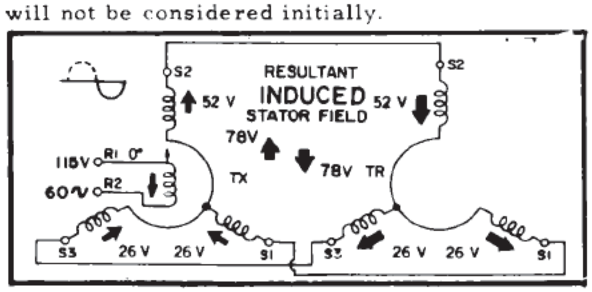


Figure 57-17 - Basic synchro system showing stator connections and induced magnetic fields (receiver rotor removed) 0° position.

A7. A synchro transmitter usually does not have an inertia damper.

In the zero position, as shown, stator windings S_1 and S_3 produce equal fields in a different direction with respect to the main field. The horizontal component of these fields cancel and the vertical components are additive and reinforce the S_2 field. Figure 57-18 is a vector representation of the stator fields existing in the transmitter at the zero position.

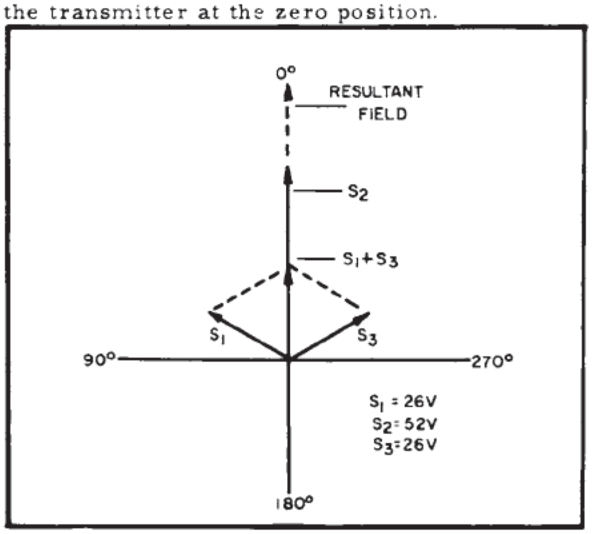


Figure 57-18 - Vector analysis. Rotor at 0°.

The S_1, S_2 and S_3 vectors are plotted to a scale proportional to 26 volts, 52 volts, and 26 volts, respectively, with the phase relationships as shown to exist during the negative alternation of the rotor excitation voltage. Since all three stator coil fields are in phase at this position, their vectors all point upward and are plotted above the horizontal axis of the graph. By constructing a parallelogram with S_1 and S_3 field vectors as the sides, the $S_1 + S_3$ resultant is shown to lie parallel to the S_2 field vector. Adding the $S_1 + S_3$ resultant to S_2, the resultant stator field vector can be determined to be proportional to 78 volts, and aligned directly along the 0° position. Note that the resultant stator field induced in the receiver is opposite to the transmitter stator field and the same as the transmitter rotor field.

In Figure 57-19, the transmitter rotor has been rotated 30° counterclockwise (30° position). Examination will show that the angular displacement between the rotor and each of the stator coils S_2 and S_1 is 30°. The induced voltage in each is found as:

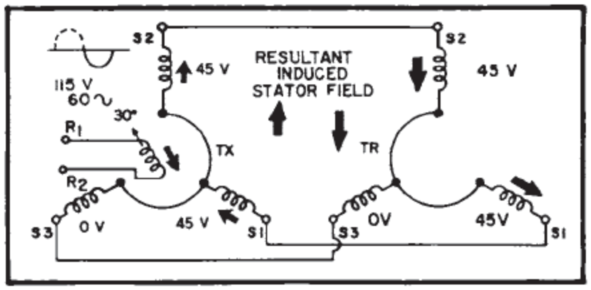


Figure 57-19 - Basic synchro system showing resultant induced stator fields (receiver rotor removed) 030° position.

$$E_{ind} = 52 \times \cos 30^\circ$$

$$E_{ind} = 52\ (0.866)$$

$$E_{ind} = 45 \text{ volts}$$

Since the rotor to the S_3 coil displacement is 90°, there is no voltage induced in the S_3 coil at the 030° position ($\cos 90^\circ = 0$). A vector analysis of the resultant transmitter stator field is given in Figure 57-20. The magnitude of the resultant field is produced by the combined effect of the S_2 field and the S_1 field. The direction of the induced receiver stator field is again seen to be opposite to the resultant transmitter stator field and the same as the transmitter rotor field.

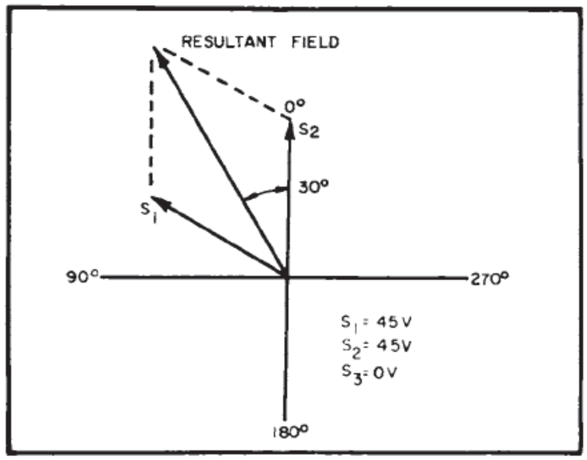


Figure 57-20 - Resultant field vector analysis. Rotor at 030°.

In figure 57-21A, the transmitter rotor has been rotated 45° counterclockwise. Figure 57-21B shows the vector solution for a condition where the transmitter rotor is positioned at 45° counterclockwise and three unequal stator voltages exist. Here, the rotor coil axis forms an angle of 15° with S_1, 45° with S_2, and 75° with S3. The induced voltage in the S1, S2, and S3 coils are 50 volts, 37 volts, and 13 volts respectively. A parallelogram constructed from the S_1 and S_2

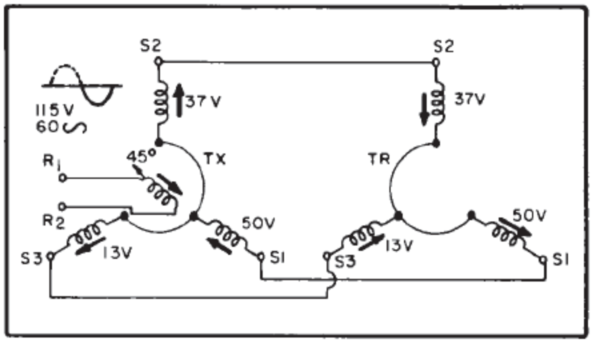


Figure 57-21A- Resultant Induced Stator Field

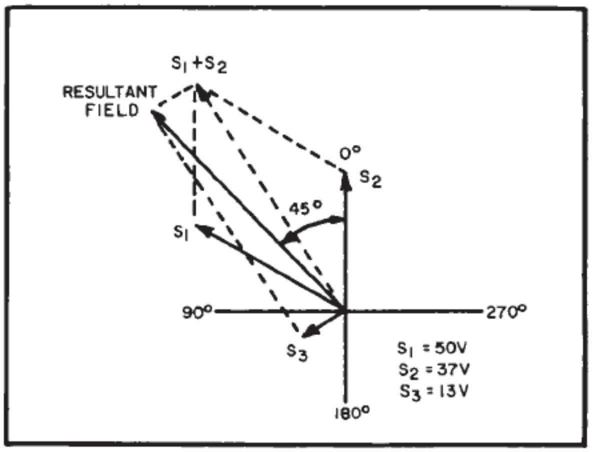


Figure 57-21B - Resultant field vector analysis. Rotor at 45°

vectors produces a resultant vector as shown. A second parallelogram is then constructed, using the $S_1 + S_2$ resultant and the S_3 vector, producing the resultant stator field which is shown to be 45° displaced from the zero position.

A standard synchro transmitter-receiver system with both transmitter and receiver rotors connected to the same 115 volt source is shown in Figure 57-22. In the illustration, the receiver rotor is restrained in a position 30° counter-clockwise from the transmitter rotor, and the induced voltages have been in-

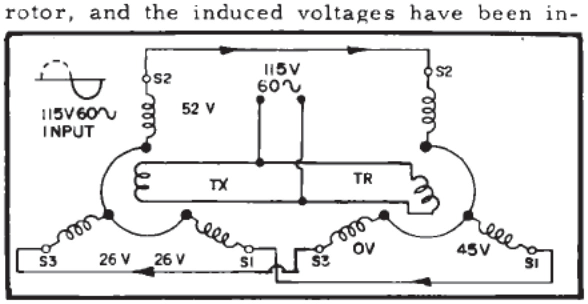


Figure 57-22 - Induced voltages and circulating stator current when receiver rotor is restrained at 30° out of correspondence.

dicated. In this unbalanced condition, current will flow in the direction shown by the arrows since potential differences exist between the induced voltages of the respective stator coils. This current sets up a resultant stator field in the receiver in such a direction as to exert a clockwise torque on the rotor of the receiver. The current will continue to flow until the rotor

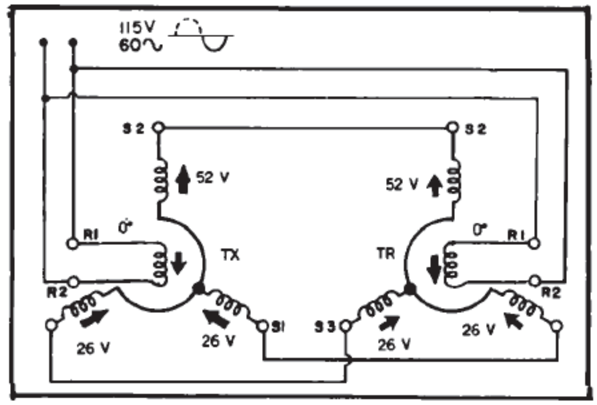


Figure 57-23 - Synchro transmitter-receiver system with rotors in correspondence, 0° position.

is permitted to align with the stator field. When alignment occurs, the voltages induced in the receiver stator coils as a result of rotor excitation will be equal and opposite to the voltages induced by the transmitter stator currents. In this balanced condition, shown in Figure 57-23, there is no current flow in the stator coils or in the interconnection, the total current flow in the system being the excitation current drawn by the two rotors. Therefore, the transmitter supplies current only when the receiver rotor is out of alignment with the transmitter rotor.

Q8. What type of excitation voltage is used for a synchro system?

Q9. Describe the relationship of the resultant magnetic field in the stator of a synchro transmitter to the rotor coil field.

Q10. Briefly explain the action of a synchro receiver rotor with respect to the transmitter rotor.

57-10. Troubleshooting Synchro Systems

Shipboard synchro troubleshooting is limited to determining whether the trouble is in the synchro, or in the system connections. You can make repairs in the system connections; but if something is wrong with the unit, replace it.

In a newly installed system, or unit, the trouble probably is the result of improper zeroing or wrong connections. Make certain all units are zeroed correctly; then check the wiring. Do not trust the color coding of the wires; check them with an ohmmeter.

In systems which have been working, the most common trouble sources are:

A8. The synchro system is excited by 115 volts, single-phase, 60 cycles or 400 cycles ac.

A9. The resultant magnetic field in the stator of a synchro transmitter is always aligned with the axis of the rotor coil field and is of opposing polarity.

A10. Due to magnetic coupling, the receiver rotor will follow the action of the transmitter rotor, provided the excitation is normal and the connections are standard.

Switches	Shorts, opens, grounds, or corrosion.
Nearby Equipment	Water or oil leaking into synchro from other devices. If this is the trouble, correct it before installing a new synchro.
Terminal Boards	Loose lugs, frayed wires, or corrosion.
Zeroing	Units improperly zeroed.

Wrong connections and improper zeroing in any system are usually the result of careless work or inadequate information. Do not rely on memory when removing or installing units. Refer to the applicable instruction book.

Most synchro systems involve units which are in widely separated locations. If trouble occurs in such a system, it must be localized as quickly as possible. To save time, use overload indicators and blown fuse indicators located on a control board to locate a faulty unit.

Tables 57-2 through 57-7 summarize, for a simple torque transmitter-torque receiver system, some symptoms and the possible causes. When two or more receivers are connected to one transmitter, similar symptoms occur. If all the receivers act up, the trouble is in the transmitter or the main bus. If the trouble appears in one receiver only, check that unit and its connection. The angles shown do not apply to systems using differentials, or to systems whose units are not zeroed, tables 57-4 through 57-7.

Q11. At what shaft position will a maximum voltage be induced in a single coil of a stator winding? (Answer on page 32)

GENERAL SYMPTOMS

Preliminary Actions: Be sure TR is not jammed physically.
Turn TX slowly in one direction and observe TR.

SYMPTOMS	TROUBLE
Overload Indicator lights. Units hum at all TX settings. One unit overheats. TR follows smoothly but reads wrong.	Rotor circuit open or shorted. See Table 3.
Overload Indicator lights. Units hum at all except two opposite TX settings. Both units overheat. TR stays on one reading half the time, then swings abruptly to the opposite one. TR may oscillate or spin.	Stator circuit shorted. See Table 4.
Overload Indicator lights. Units hum on two opposite TX settings. Both units get warm. TR turns smoothly in one direction, then reverses	Stator circuit open. See Table 5.
TR reads wrong, or turns backward, follows TX smoothly.	Unit interconnections wrong. Unit not zeroed. See Tables 6& 7

TABLE 57-2 - Synchro troubles.

OPEN OR SHORTED ROTOR

Preliminary Action: Set TX to 0° and turn rotor smoothly counterclockwise.

SYMPTOMS	TROUBLE
TR turns counterclockwise from 0 to 180° in a jerky or erratic manner, and gets hot.	TX rotor open.
TR turns counterclockwise from 0 or 180° in a jerky or erratic manner. TX gets hot.	TR rotor open.
TR turns counterclockwise from 90 or 270°, torque is about normal, motor gets hot, TX fuses blow.	TX rotor shorted.
TR turns counterclockwise from 90 or 270°, torque is about normal, TX gets hot, TR fuses blow	TR rotor shorted.

TABLE 57-3 - Synchro troubles.

SHORTED STATOR		
SYMPTOMS		TROUBLE
Setting or Conditions	Indication	
When TX is on 120° or 300° but When TX is between 340° and 80°, or between 160° and 260°	Overload Indicator goes out and TR reads correctly. Overload Indicator lights, units get hot and hum, and TR stays on 120° or 300° or may swing suddenly from one point to the other.	Stator circuit shorted from S_1 to S_2.
When TX is on 60° or 240° but When TX is between 280° and 20°, or between 100° and 200°	Overload Indicator goes out and TR reads correctly. Overload Indicator lights, units get hot and hum, and TR stays on 60° or 240° or may swing suddenly from one point to the other.	Stator circuit shorted from S_2 to S_3. Stator circuit shorted from S_2 to S_3.
When TX is on 0° or 180° but When TX is between 40° and 140°, or between 220° and 320°	Overload Indicator goes out and TR reads correctly. Overload Indicator lights, units get hot and hum, and TR stays on 0° or 180° or may swing suddenly from one point to the other.	Stator circuit shorted from S_1 to S_3. Stator circuit shorted from S_1 to S_3.
	Overload Indicator on continuously, both units get very hot and hum, and TR does not follow at all or spins.	All three stator leads shorted together.

TABLE 57-4 - Synchro troubles.

OPEN STATOR		
SYMPTOMS		TROUBLE
Setting or Conditions	Indication	
When TX is on 150° or 330° When TX is held on 0°	TR reverses or stalls and Overload Indicator lights. TR moves between 300° and 0° in a jerky or erratic manner.	S_1 stator circuit open.
When TX is on 90° or 270° When TX is held on 0°	TR reverses or stalls and Overload Indicator lights. TR moves to 0° or 180°, with fairly normal torque.	S_2 stator circuit open.
When TX is on 30° or 210° When TX is held on 0°	TR reverses or stalls and Overload Indicator lights. TR moves between 0° and 60° in a jerky or erratic manner.	S_3 stator circuit open.
When TX is set at 0°, and then moved smoothly counter-clockwise	TR does not follow, no Overload Indication, no hum or overheating.	Two or three stator leads open or both rotor circuits open.

TABLE 57-5 - Synchro troubles.

WRONG STATOR CONNECTIONS, ROTOR WIRING CORRECT These problems must be worked using a stationary pointer on the chassis and a compass card mounted on the rotor.		
Setting or Conditions	Indication	Trouble
TX set to 0° and rotor turned smoothly counterclockwise	TR indication is wrong, turns clockwise from 240°.	S_1 and S_2 stator connections are reversed.
	TR indication is wrong, turns clockwise from 120°.	S_2 and S_3 stator connections are reversed.
	TR indication is wrong, turns clockwise from 0°.	S_1 and S_3 stator connections are reversed.
	TR indication is wrong, turns counterclockwise from 120°	S_1 is connected to S_2, S_2 is connected to S_3, and S_3 is connected to S_1.
	TR indication is wrong, turns counterclockwise from 240°.	S_1 is connected to S_3, S_2 is connected to S_1, and S_3 is connected to S_2.

TABLE 57-6 - Synchro troubles.

WRONG STATOR AND/OR REVERSED ROTOR CONNECTIONS These problems must be worked using a stationary pointer on the chassis and a compass card mounted on the rotor.		
Setting or Conditions	Indication	Trouble
TX is set to 0° and rotor turned smoothly counterclockwise	TR indication is wrong, turns counterclockwise from 180°.	Stator connections are correct, but rotor connections are reversed.
	TR indication is wrong, turns clockwise from 60°.	Stator connections S_1 and S_2 are reversed, and rotor connections are reversed.
	TR indication is wrong, turns clockwise from 300°.	Stator connections S_2 and S_3 are reversed, and rotor connections are reversed.
	TR indication is wrong, turns clockwise from 180°.	Stator connections S_1 and S_3 are reversed, and rotor connections are reversed.
	TR indication is wrong, turns counterclockwise from 300°.	S_1 is connected to S_2, S_2 is connected to S_3, S_3 is connected to S_1, and rotor connections are reversed.
	TR indication is wrong, turns counterclockwise from 60°.	S_1 is connected to S_3, S_2 is connected to S_1, S_3 is connected to S_2, and rotor connections are reversed.

TABLE 57-7 - Synchro troubles.

Q12. How are the rotors of synchro transmitters and receivers connected?

57-11. Differential Synchro Transmitters (TDX)

The stator of a differential is similar to that of the simple transmitters and receivers discussed in preceding sections of this chapter. It consists of the usual three sets of coils wound around the inside of the stator frame, and connected to produce poles 120° apart electrically. The three windings are wye connected and make contact with external circuitry through a set of three slip rings mounted on the rotor shaft. The rotor, shown in Figure 57-24, is quite different from the rotor of a conventional synchro unit, both physically and electrically. The differential rotor is cylindrical, rather than bobbin-shaped, and more closely resembles a wound generator armature. Electrically, there are three sets of coils wound in slots equally spaced around the rotor and connected to produce poles 120° apart. A schematic representation of the differential transmitter is shown in Figure 57-25.

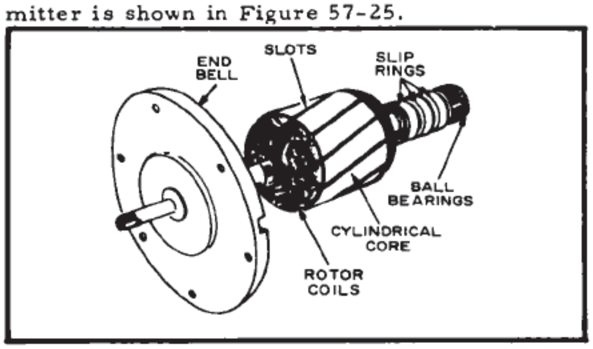


Figure 57-24 - Differential transmitter rotor.

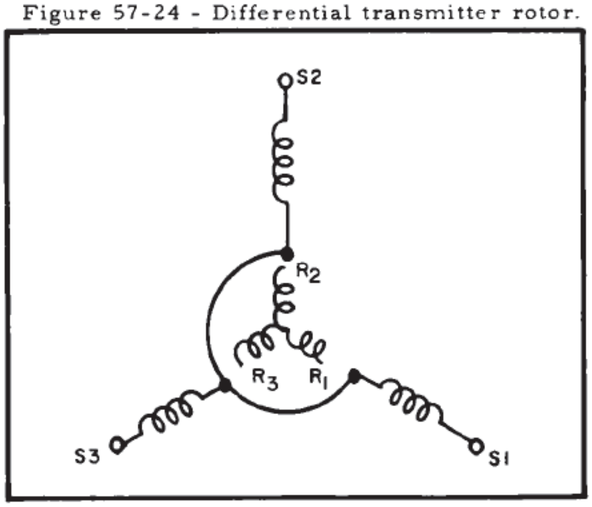


Figure 57-25 - Schematic of differential synchro.

The stator is the primary, and receives its excitation from a synchro transmitter. The voltage appearing across the differential's rotor terminals are determined by the magnetic field created by the stator currents and the physical position of the rotor. The magnetic field created by the stator currents assumes an angle corresponding to that of the magnetic field in the transmitter supplying the excitation. If the rotor position changes, the voltages induced into its windings also change, so that the voltages present at the rotor terminals change.

Assume that the stator leads of a torque transmitter are connected to the corresponding stator leads of a torque differential transmitter, as shown in Figure 57-26.

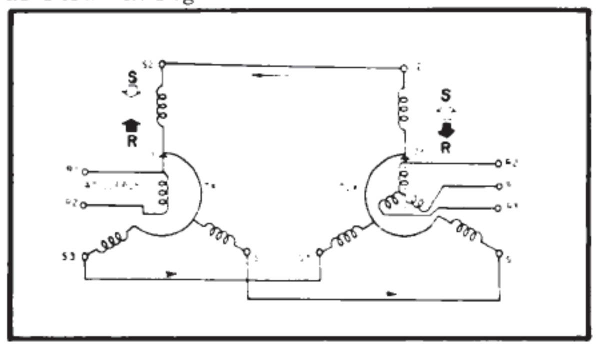


Figure 57-26 - Position of TDX stator mmf when rotor is at zero degrees.

The resultant stator mmf, shown by the open arrow, produced in the TX directly opposes the TX rotor mmf, shown by the solid arrow. Corresponding stator coils of the two units are in series; for example, S_2 of TX is in series with S_2 of the TDX, and the current flow produces a resultant stator mmf of equal strength in the TDX. However, currents in corresponding stator coils of the TDX are opposite in direction, the direction of the stator mmf, but identical to the direction of its rotor mmf.

The TDX rotor coils are angularly spaced 120° apart, in the same manner as the TX stator coils. The TDX stator mmf is identical to the TX rotor mmf, neglecting small circuit losses.

Before considering such an arrangement, however, it must be made clear that the controlling relationship in the TDX is the position of the TDX field with respect to the TDX stator. Suppose that the TX rotor in the previous example is turned to 75 degrees, and the TDX rotor to 30 degrees, as shown in Figure 57-27. The TDX stator field is now positioned at 75° with respect to S_2, but the angle at which it cuts the TDX rotor is 45°, using the R_2 axis as a reference. This is the angle which determines the signal which the TDX transmits. Notice that turning the TDX rotor 30° counterclockwise decreased the angle between the TDX stator field and R_2 by that amount.

Q13. What effects might be noted if the rotor winding of a synchro receiver was open?

A11. The maximum voltage will be induced in a stator coil when the rotor coil is parallel (aligned) with the stator coil.

A12. The rotors of synchro transmitters and synchro receivers are connected in parallel with a common source.

A13. If the rotor winding of a synchro receiver is open, the receiver will follow the transmitter but may be 180° in error.

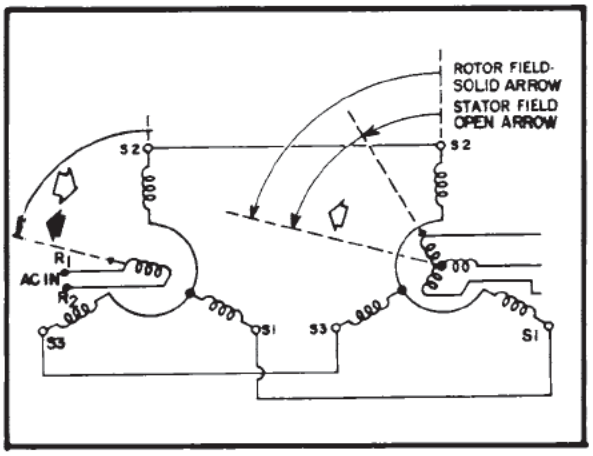


Figure 57-27 - Rotating TDX stator field by turning the TX rotor.

A14. What is the main function of the minimum current that is drawn by the rotors of synchro units at correspondence?

A15. Describe the null condition of a synchro system.

57-12. TX-TDX-TR Synchro System

The manner in which the torque system containing a TDX subtracts or adds two inputs can be described as the positioning of magnetomotive forces. Figure 57-28 shows such a system connected for subtraction. A mechanical input of 75 degrees is applied to the TX and converted to an electrical signal which the TX transmits to the TDX stator. The TDX subtracts its own mechanical input from this signal, and transmits the result to the TR, which indicates the torque system's mechanical output by the position of its rotor.

To understand how this result is accomplished, first consider the conditions in a TX-TDX-TR system when the TX and TDX rotors are turned to zero degrees, as in Figure 57-29.

It has been shown how torque is developed in a synchro receiver to bring its rotor into a position which corresponds to that of an associated transmitter. The rotor voltages of the TDX depends upon the position of the magnetic field in relation to the rotor windings in the same way that the stator voltages of a TR depend on the position of the magnetic field in relation to the TR stator windings. The TDX stator field axis orients itself in the TDX stator in the same relative position that the TX rotor axis is oriented in its stator. The TR rotor therefore follows the angular position of the TDX stator field with respect to R_2 of the TDX. Since this is zero degrees, the TR rotor turns to that position, and indicates zero degrees.

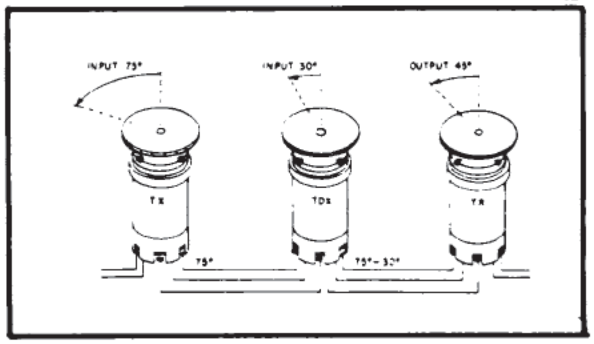


Figure 57-28 - Subtraction with TDX.

Frequently it is necessary to set up a TX-TDX-TR system for addition. This is done by reversing the S1 and S3 leads from the TX to TDX stators and from the TDX rotor to TR stators. With these connections, the system behaves as illustrated in Figure 57-30. The 75 and 30 degree mechanical inputs, applied respectively to the rotor of the TX and the rotor of the TDX, are added and transmitted to the TR, whose rotor provides an output equal to their sum by turning to 105 degrees.

57-13. Differential Synchro Receiver (TDR)

As previously explained, the differential receiver differs chiefly from the differential transmitter in its application. The TDX in each of the previous examples combined its own input with the signal from a synchro transmitter and transmitted them the sum or difference to a synchro receiver, which provided the system's mechanical output. In the case of the differential receiver in a torque system, the differential unit itself provides the system's mechanical output, usually as the sum or difference of the electrical signals received from two synchro transmitters. Both rotor and stator receive energizing currents from torque transmitters. The two resultant magnetic fields interact and the rotor turns.

In a torque differential synchro system, the

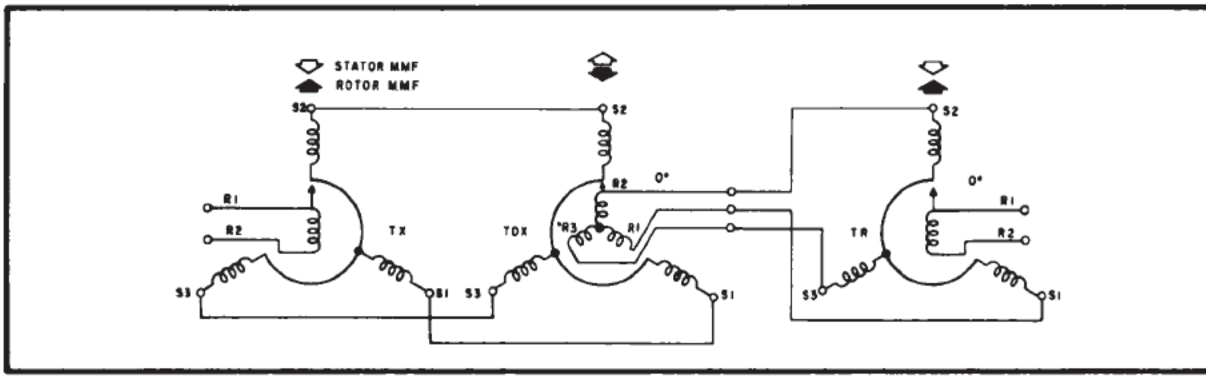


Figure 57-29 - Magnetomotive force positions in TX-TDX-TR system with all rotors at zero degree.

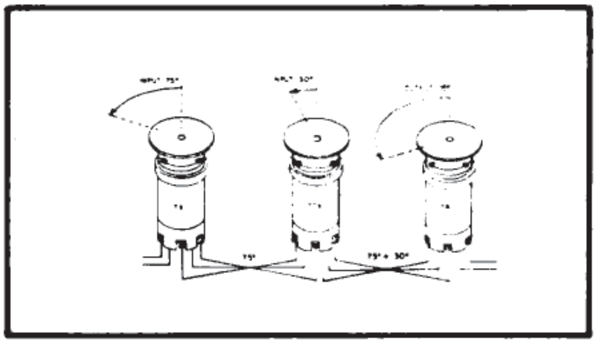


Figure 57-30 - Addition with TDX.

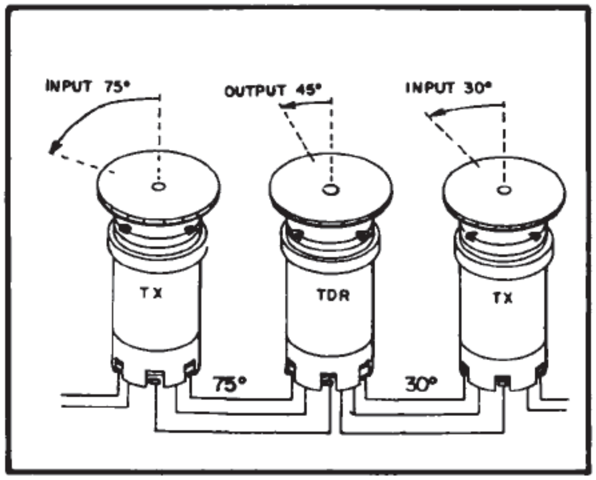


Figure 57-31 - Subtraction with TDR.

system will consist either of a torque transmitter (TX), a torque recevier (TR); or the system may consist of two torque transmitters (TX) and one torque differential receiver (TDR).

Figure 57-31 shows a system consisting of two torque transmitters and a differential receiver connected for subtraction.

In considering the operation of the TDR, it is important to remember that its rotor currents do not flow as a direct result of the rotor voltages induced by the fluctuating stator field, but only as a result of an unbalance between these induced voltages and the induced stator voltages of the TX to which the TDR rotor is connected. When the rotor is turned, its stator voltages are changed, and current flows in both the TX stator and the TDR rotor coils. The TDR rotor field established by these currents rotates in the same direction, with respect to R_2, as the TX rotor. Unless the rotor of the TX connected to the TDR stator is turned by an equal amount, the TDR rotor and stator fields are displaced with respect to each other, and a strong magnetic torque immediately operates to bring the two fields back into alignment. Since the TDR rotor is free to move, it rotates accordingly, restores the voltage balance in the TDR rotor circuits, and reduces current flow to a low value.

The signal from the TX connected to the TDR stator rotates the resultant stator field 75 degrees counterclockwise. In a similar manner, the signal from the other TX to the TDR rotor rotates the resultant rotor field counterclockwise 30° with respect to R_2. However, since the two resultant fields are not rotated by equal amounts, torque is developed to bring them into alignment. The rotor therefore turns to 45 degrees, at which point the two fields are aligned. To bring its resultant field into alignment, the TDR rotor need only be turned through an angle equal to the difference between the signals supplied by the two TX's. This is the requirement of the system.

To set up the system just considered for addition of the inputs to the two TX's, it is only necessary to reverse the R_1 and R_3 leads between the TDR rotor and the TX to which it is connected. With these connections reversed,

A14. The rotor of a synchro must continuously draw current to remain magnetized.

A15. Synchro systems will be at a null when induced EMF's are out of phase and equal.

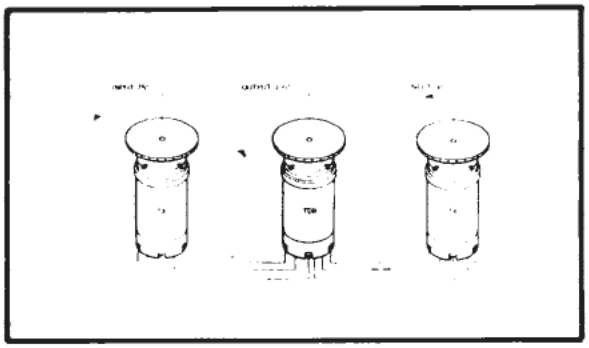


Figure 57-32 - Addition with TDR.

the system operates as shown in Figure 57-32.

Figure 57-33 illustrates how resultant magnetic fields are positioned to produce this effect, again assuming that the TDR rotor is initially at 0 degrees, while the two TX rotors are turned from 0° to 75° and 30° respectively.

The TDR stator field still rotates counterclockwise 75°, but because of the reversed R_1 and R_3 connections of the TDR rotor, the rotor field rotates 30° clockwise. The angular displacement of the two fields with respect to each other, then, is the sum of the signals transmitted by the two TX's; and the magnetic force pulling the TDR rotor field into alignment with that of the stator turns the TDR to 105°.

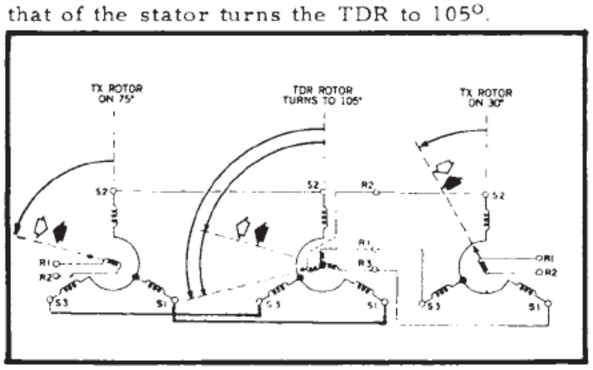


Figure 57-33 - Effect of turning both TX rotors in TX-TDR-TX system connected for addition.

Q16. Name the inputs and outputs of a differential receiver.

57-14. Control Transformer (CT)

The comparatively small mechanical output of a torque synchro system is suitable only for very light loads; and even when it is not heavily loaded, a torque system is never entirely accurate. The receiver rotor requires a slight amount of torque to overcome its static friction, and this torque can only be produced by a small error in the system. In addition, torque systems place a drag on associated equipment, which affects their accuracy.

When larger amounts of power and a higher degree of accuracy are required as in the training mechanism of a heavy radar antenna, torque synchro systems give way to control synchros used as components of zero systems. Synchros control, servos provide power.

The distinguishing unit of any control system is the control transformer, CT. The CT is a synchro designed to supply, from its rotor terminals, an ac voltage with magnitude and phase dependent on the signal applied to the three stator windings. Magnetizing current is supplied to the stator windings from either a transmitter, CX or TX, or differential transmitter, CDX or TDX. The magnetic field created by the stator currents corresponds in position to the position of the field in the synchro supplying the excitation. By transformer action, a voltage is induced in the rotor or secondary winding. The amplitude and phase of the induced voltage depends on the angular displacement of the CT rotor in respect to the rotor of the transmitter unit. When the two rotor positions correspond, the voltage across the CT rotor is minimum.

The behavior of the CT in a system differs from that of the synchro units previously considered in several important respects.

Since the rotor winding is never connected to the ac supply, it induces no voltages in the stator coils. As a result, the CT stator currents are determined only by the voltages applied to the high impedance windings. The rotor itself is wound so that rotor position has very little effect on the stator currents. Also there is never any appreciable current flowing in the rotor because its output voltage is always applied to a high impedance load. Therefore, the rotor does not turn to any particular position when voltages are applied to the stators. The rotor shaft of a CT is always turned by an external force, and produces varying output voltages from its rotor winding. Like synchro transmitters, the CT requires no inertia damper; but unlike either transmitters or receivers, rotor coupling to S_2 is minimum when the CT is at the 0° position.

Figure 57-34 shows the conditions existing in the system when a CT is connected for operation with a CX (control transmitter) and the rotors of both units are positioned at zero degrees. The relative phases of the individual stator voltages with respect to the R_1 to R_2

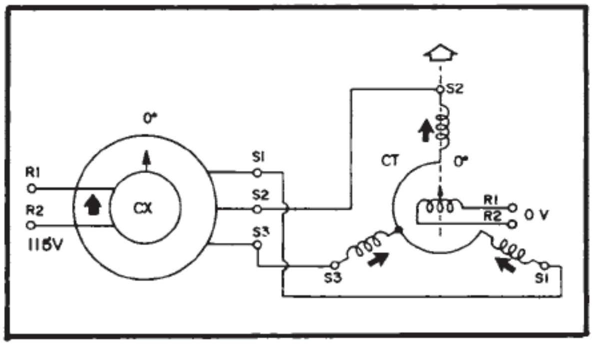


Figure 57-34 - Conditions in CX-CT system with rotors in correspondence.

voltage of the transmitter are indicated by the small arrows. The resultant stator field of the CT is shown in the same manner as for the TDX. With both rotors in the same position, the CT stator field is at right angles to the axis of the rotor coil. Since no voltage is induced in a coil by an alternating magnetic field perpendicular to its axis, the output voltage appearing across the rotor terminals of the CT is zero.

If the CT rotor is turned to 90°, as in Figure 57-35, while the CX rotor remains aligned with S_2, the axis of the rotor coil will be in alignment with the stator field. Maximum voltage, approximately 55 volts, is then induced in the coil and appears across the rotor terminals as the output of the CT.

If the CX rotor is turned to 180°, as in Figure 57-36, the electrical positions of the CX and CT would be 90° apart. The CT stator field and rotor axis are aligned, and the CT's output is maximum again, but the direction of the rotor's winding is now reversed with respect to the direction of the stator field. The phase of the output voltage is therefore opposite to that of the CT in the preceding example. This means that the phase of the CT's output voltage indicates the direction in which the CT rotor is displaced with respect to the position-data signal applied to its stators.

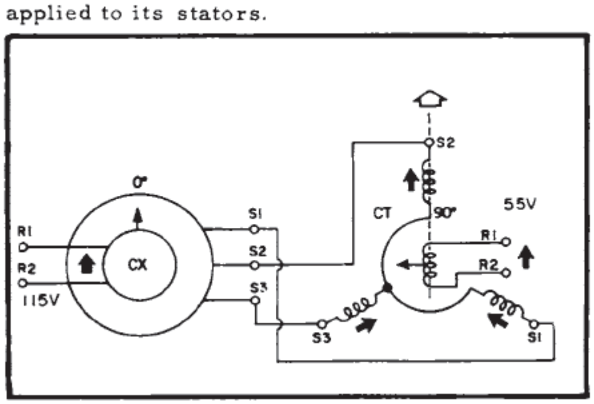


Figure 57-35 - Conditions in CX-CT system with CX rotor at 0° and CT rotor at 90°.

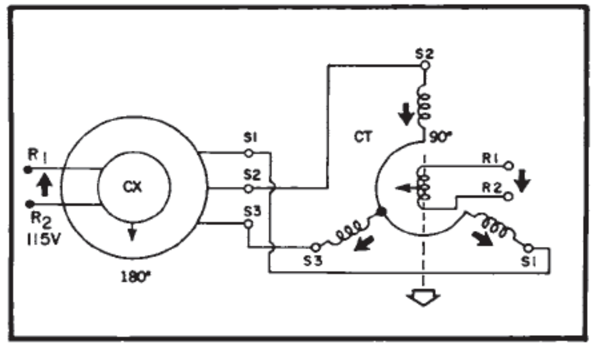


Figure 57-36 - Conditions in CX-CT system with CX rotor at 180° and CT rotor at 90°.

It is evident that the CT's output can be varied by rotating either its rotor or the position-data signal applied to its stators. It can also be seen that the magnitude depends on the phase relationship between signal and rotor rather than on the actual position of either.

Q17. Describe the output of a synchro control transformer.

Q18. How do the rotor and stator impedances of a control transformer compare with those of standard synchro transmitters and receviers?

57-15. Synchro Capacitor

Since in ac circuits, the current through a coil does not reverse at the same time as the applied voltage, the current in synchro circuits will, likewise, reverse after or lag the voltage by an amount of time determined by a synchro coil impedance. When a differential or control transformer is connected to a transmitter, the transmitter must supply the stator currents to the other synchro. The total current supplied is the sum of two lesser currents, (1) the loss current, in phase with the applied voltage, which supplies the heat loss in the windings and laminations, and (2) the magnetizing current, lagging the applied voltage by 90°, which produces the magnetic field. Figure 57-37 shows the relationship of these currents and the equivalent circuit

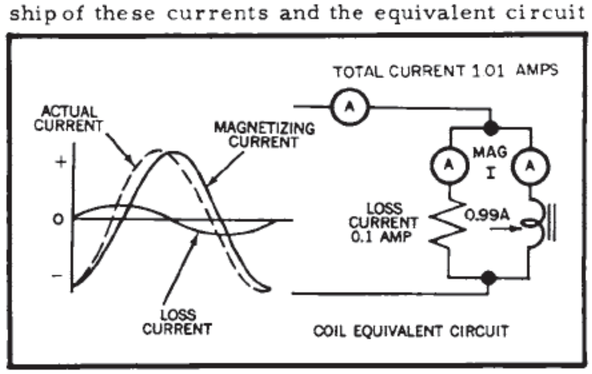


Figure 57-37 - Coil currents.

A16. The differential receiver has two inputs, both electrical, and one mechanical output.

A17. The control transformer output is an electrical voltage representative of a shaft position.

A18. The control transformer has higher rotor and stator impedances than a synchro transmitter or receiver of equivalent size.

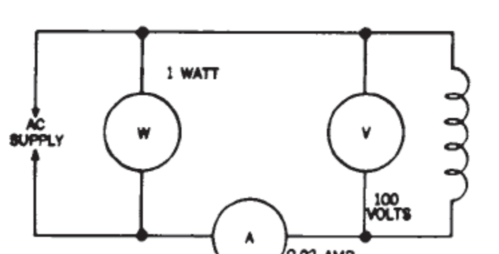
of the coil.

Because the currents are not in phase, the effective value of the actual current is less than the sum of the two effective values.

By the same token, the effective power of a circuit in which the voltage and current are out of phase is less than the volt-ampere product. As an example, in Figure 57-38, the wattmeter indicates that the power supplied to the coil is one watt, while the volt-ampere product is two volt-amperes. As illustrated, power factor is normally expressed as a percentage; it cannot exceed 100%.

The current drawn by a coil can be reduced by connecting a capacitor across it. In a capacitor, the current leads the applied voltage. In Figure 57-39, the capacitor used draws a current equal to the magnetizing current of the coil. The two out-of-phase currents cancel, and the actual current is only the loss current.

A synchro capacitor consists of three equal delta-connected capacitors. If these capacitors are connected in parallel with the stator winding of a synchro differential or control transformer, the stator current drawn from the transmitter is reduced so that under no-load conditions the transmitter supplied only loss current.



POWER FACTOR = $\frac{W}{VA}$ X 100%

WHERE: W IS THE ACTUAL POWER AS MEASURED BY THE WATTMETER
V IS THE INDICATED VOLTAGE
A IS THE INDICATED CURRENT

IN THE ILLUSTRATION:

POWER FACTOR = $\frac{1}{100 \times 0.02}$ X 100% = 50%

Figure 57-38 - Power factor.

The capacitor should be mounted as close as possible to the control transformer or differential with which it is used; high currents in long lead runs increase the transmitter load and reduce the system accuracy. Figure 57-40 shows a typical use of synchro capacitors.

Q19. What is the purpose of a synchro capacitor?

57-16. Zeroing

If synchros are to work together properly in a system, it is essential that they be correctly connected and aligned in respect to each other, and to the other devices with which they are used.

Electrical zero is the reference point for alignment of all synchro units. The mechanical reference point for the units connected to the synchros depends upon the particular application of the synchro system. When a synchro system is used to repeat ship's course data, the reference point would be true north. For radar or sonar equipments, the reference point could be the ship's bow or zero degrees. In a range or azimuth data transmission system, a specific distance or angle could be the reference point. What ever the system, the electrical and mechanical reference points must be aligned. ZEROING a synchro means adjusting it mechanically so that it will work properly in a system in which all other synchros are zeroed.

A synchro transmitter, CX or TX, is zeroed if electrical zero voltages exist when the unit whose position the CX or TX transmits is set to its mechanical reference position. A synchro receiver, TR, is zeroed if, when electrical zero voltages exist, the device actuated by the receiver assumes its mechanical reference position. In a receiver or other unit having a rotatable stator, the zero position is the same, with the added provision that the unit to which the stator is geared is set to its reference position. In the electrical zero position, the axes of the rotor coil and the S_2 coil are at zero displacement and the voltage measured between terminals S_1 and S_3 will be minimum. The voltages from S_2 to S_1 and from S_2 to S_3 are in phase with the excitation voltage from R_1 to R_2. The actual terminal voltage should be as listed in Table 57-8.

A differential is zeroed if the unit can be inserted into a system without introducing a change in the system. In the electrical zero position the axes of coils R_2 and S_2 are at zero displacement. Terminal voltages are as listed in Table 57-9.

A synchro control transformer is zeroed if its rotor voltage is minimum when electrical zero voltages are applied to its stator, and

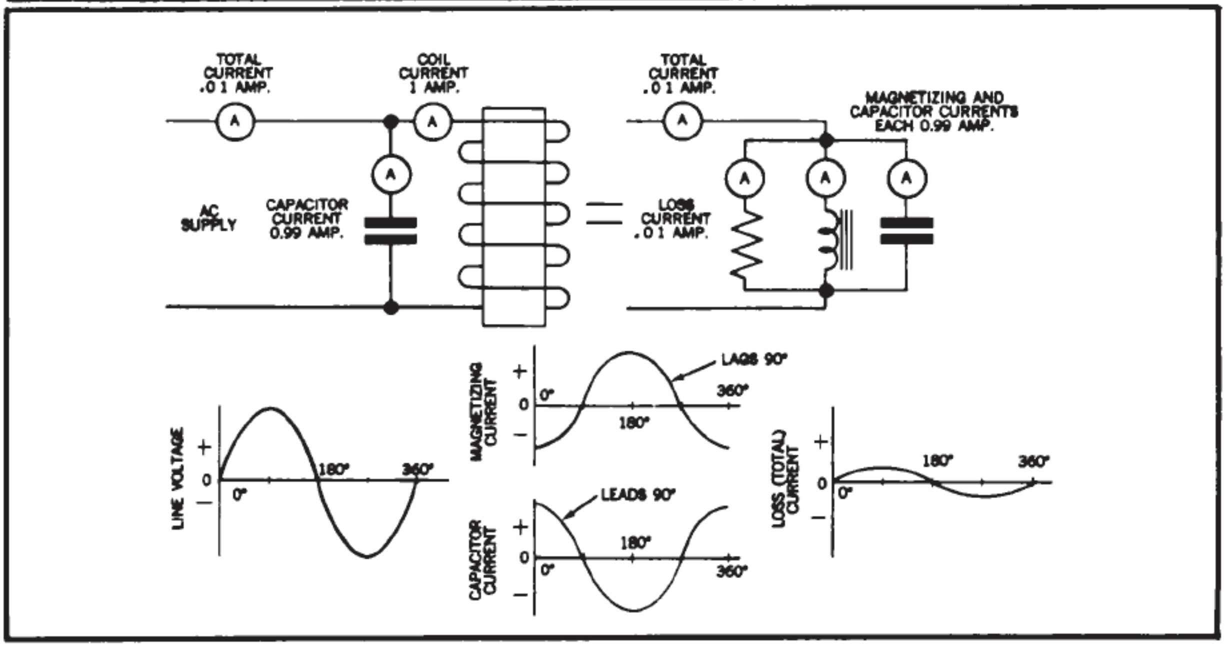


Figure 57-39 - Effect of capacitor on coil currents.

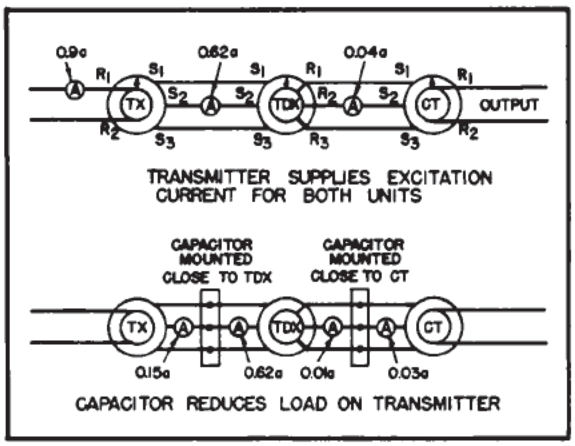


Figure 57-40 - Use of synchro capacitors.

turning the CT's shaft slightly counterclockwise produces a voltage between R_1 and R_2 which is in phase with the voltage between R_1 and R_2 of the CX or TX supplying excitation to the CT stator. Electrical zero voltages, for the stator only, are the same as for transmitters and receivers.

The procedure used for zeroing depends upon facilities and tools available and how the synchros are connected in the system. Regardless of the methods used, there are two major steps in each zeroing procedure. First, the coarse or approximate setting and second, the fine setting. Many units are marked in such a manner that the coarse setting is approximated physically. On standard units, an arrow or dot is stamped on the frame and a line is marked on the shaft extension.

115-volt Synchro		26-volt Synchro	
R_1 to R_2	115 volts	R_1 to R_2	26 volts
S_2 to S_1	78 volts	S_2 to S_1	10. 2 volts
S_2 to S_3	78 volts	S_2 to S_3	10. 2 volts
S_1 to S_3	zero volts	S_1 to S_3	zero volts

Table 57-8 - Actual synchro terminal voltages.

115-volt Synchro		26-volt Synchro	
R_1 to R_3	zero volts	R_1 to R_3	zero volts
S_1 to S_3	zero volts	S_1 to S_3	zero volts
R_3 to R_2	78 volts	R_3 to R_2	10. 2 volts
S_3 to S_2	78 volts	S_3 to S_2	10. 2 volts
R_2 to R_1	78 volts	R_2 to R_1	10. 2 volts
S_2 to S_1	78 volts	S_2 to S_1	10. 2 volts

Table 57-9 - Actual synchro terminal voltages.

A19. The synchro capacitor is used to cancel I_{X_L} in the stator circuits of systems using differential units and/or control transformers.

Q20. Describe the electrical zero condition of a synchro transmitter or receiver.

57-17. Zeroing a Transmitter, CX or TX, Using a Voltmeter

The most accurate results can be obtained by using an electronic or precision voltmeter having 0 to 250 and 0 to 5 volt ranges. On the 0 to 5 volt range the meter should be able to measure voltages as low as 0.1 volt. Proceed as follows:

1. Set the unit, whose position the CX or TX transmits, accurately in its zero position.

2. Remove all other connections from the transmitter's stator leads.

3. Connect meter as shown in Figure 57-41.

4. Adjust rotor or stator for null, minimum reading.

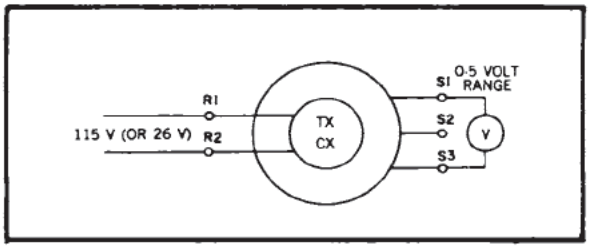


Figure 57-41 - Zeroing a TX or CX using a voltmeter.

57-18. Zeroing Torque Receiver with Rotor Not Free to Turn

When a torque receiver rotor is not free to turn, it is necessary to zero it in a manner similar to that used for transmitters. A check on receiver zeroing may be made as follows:

1. Set the transmitter to the electrical zero position and connect a temporary jumper from S_1 to S_3, Figure 57-42. If the receiver's shaft moves more than a fraction of a degree when the jumper is connected, the transmitter is not set on 0 degrees and should be rechecked.

2. If receiver shaft does not turn, unclamp synchro and rotate it until the receiver

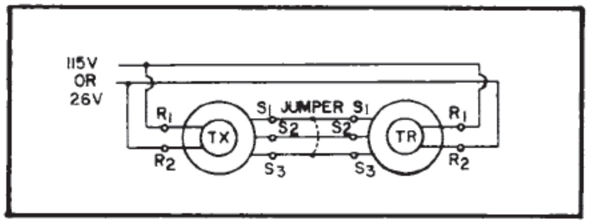


Figure 57-42 - Zeroing a TX using a TR.

2. (continued) dial reads zero. Connecting and disconnecting the jumper several times so that the dial moves slightly, may help to set the dial more accurately.

3. Clamp the receiver in position when finished and remove the jumper.

57-19. Zeroing a Synchro Receiver by Electrical Lock

If lead connections may be easily removed, remove all stator connections and reconnect as shown in Figure 57-43. The shaft will turn definitely to 0 degrees. Set the dial at its zero or reference position while the receiver is connected this way. If a source of 78 volts (10.2 volts for 26 volt units) is not available, 115 volts (15 volts for 26 volt units) may be connected to R_1 and R_2 provided that it is not left connected in this manner for more than 1 or 2 minutes, because operation on higher than the rated voltage causes the synchro to overheat.

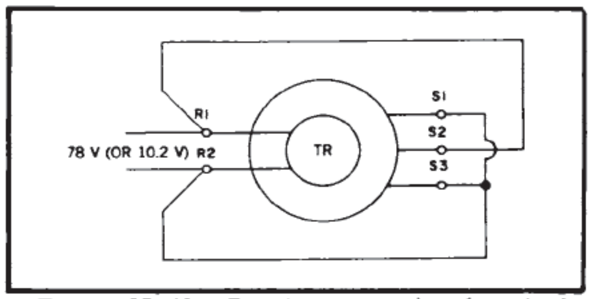


Figure 57-43 - Zeroing torque by electrical lock.

57-20. Zeroing a Torque Receiver, TR, with a Free Rotor

To zero a torque receiver with a free rotor proceed as follows:

1. Disconnect stator leads and note normal connections for use when reconnecting.

2. Set voltmeter on 0 to 250 volt scale and connect as shown in Figure 57-44A.

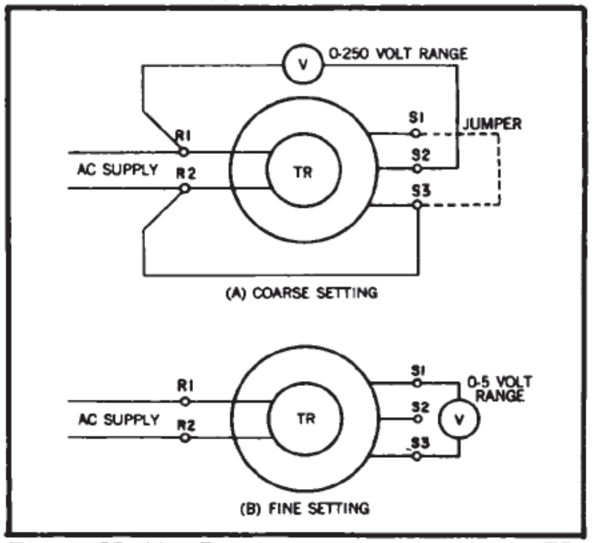


Figure 57-44 - Zeroing a torque receiver, TR, with a free rotor.

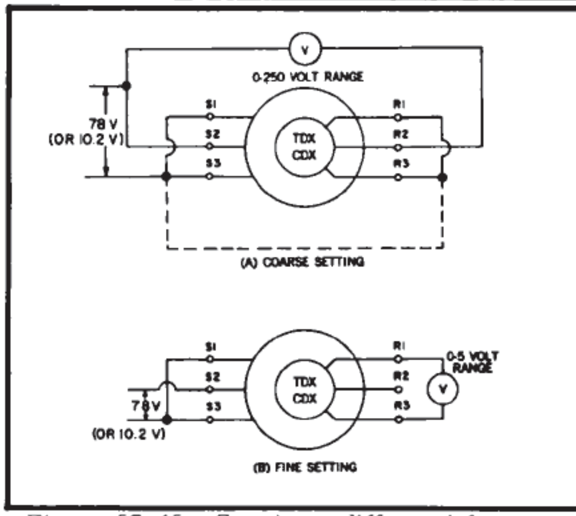


Figure 57-45 - Zeroing a differential transmitter using a voltmeter.

3. Temporarily, connect jumper between S_1 and S_3 as shown by dotted line. Rotor will turn to 0 or 180°; if meter reads about 40 volts, 15 volts for 26 volt synchros, rotor is at 0°; proceed with step 4. If meter reads about 150 volts, 38 volts for 26 volt units, rotor is at 180°; with jumper disconnected between S_1 and S_3, turn rotor to approximate zero setting. Reconnect jumper; now synchro should go to 0 degrees; if meter reads 40 volts, 15 volts for 26 volt synchros, proceed with step 4.

4. Connect meter as shown in Figure 57-44B.

5. Adjust rotor or stator for minimum voltmeter reading.

57-21. Zeroing a Differential Transmitter Using a Voltmeter

A differential transmitter may be most accurately zeroed by using an ac voltmeter having 0 to 250 and 0 to 5 volt ranges. The procedure is as follows:

1. Set the unit, whose position the CDX or TDX transmits, accurately in its zero or reference position.

2. Remove all other connections from the differential leads, set the voltmeter on its 0 to 250 volt scale, and connect as shown in Figure 57-45A

3. Unclamp the differential and turn it until the meter reads minimum. The differential is now on approximate electrical zero. Reconnect as shown in Figure 57-45B.

4. Set the voltmeter on the 0 to 5 volt scale and turn the differential transmitter in this position until a null reading is obtained. Clamp the differential in this position and reconnect all leads for normal operation.

57-22. Zeroing a Control Transformer, Using an AC Voltmeter

Using a voltmeter with a 0 to 250 and 0 to 5 volt scale, control transformers may be zeroed as follows:

1. Remove connections from control transformer and reconnect as shown in Figure 57-46A.

2. Turn rotor or stator to obtain minimum voltage readings.

3. Reconnect meter as shown in Figure 57-46B and adjust rotor or stator for minimum reading.

4. Clamp the control transformer in position and reconnect all leads for normal use.

57-23. Step-by-Step System

The synchros and similar devices thus far discussed are used with alternating currents. At times, remote indicating systems which oper-

A20. Conditions of electrical zero in a synchro are zero volts between S_1 and S_3; R_1 and S_2 in phase.

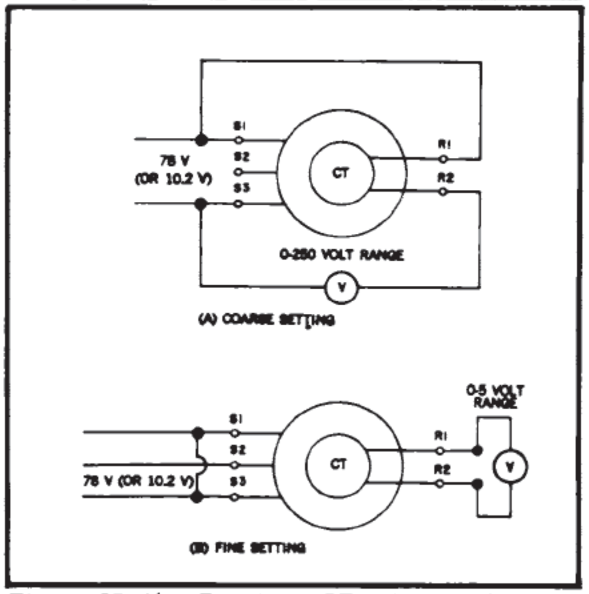


Figure 57-46 - Zeroing a CT using a voltmeter.

ate on direct current are required. One of these the STEP-BY-STEP system, is illustrated in Figure 57-47. Although many variations are employed, the system shown is typical.

The step-by-step system is often used to drive compass repeaters on naval vessels and merchant ships having dc power.

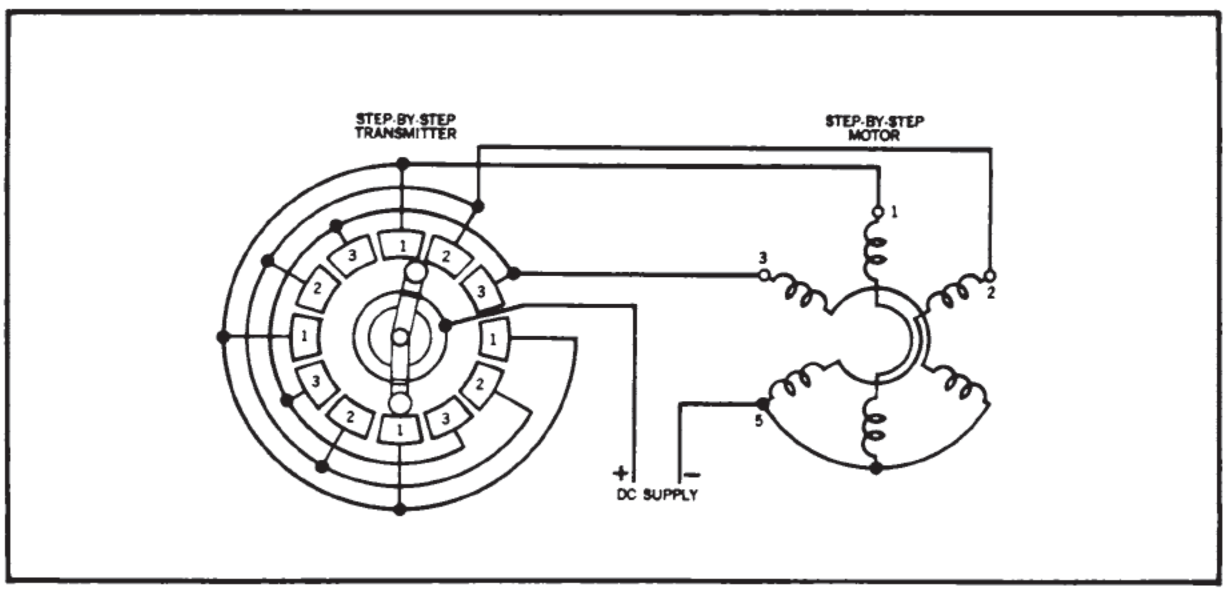
The principles of operation of the step-by-step motor are very much the same as discussed in Chapter 56. Six electromagnets are mounted around a soft iron armature and connected as shown in Figure 57-48. Each pair of coils is wound opposite to the adjacent pair.

If a dc voltage is applied across the number 1 coils, the armature turns to the position shown in Figure 57-49A. Since the armature is soft iron, either end may turn up, depending upon the position of the rotor when voltage is applied. If the same voltage is also applied to the number 2 coils, the armature turns to a position midway between the number 1 and number 2 coils as shown in Figure 57-49B. If the number 1 coils are now disconnected, the armature turns until it lines up with the number 2 coils as shown in Figure 57-49C. Figure 57-49D shows the number 3 coils connected and the armature rotated one step further. If this process is continued as shown in Figure 57-49E and F, the armature can be rotated through 360°.

In actual operation, the step-by-step motor is driven by a rotary switch shown in Figure 57-50. As the switch rotates, it applies voltage first to coil 1; then to coils 1 and 2 together; then to coil 2; and then to coils 2 and 3 together; then to 3 and so on until the complete revolution is made. As a result, the armature turns in 30° steps following the rotation of the rotary switch. The rotating arm of the switch is geared to the gyro compass so that 1 degree rotation of the gyro causes the rotary arm to rotate through 360°. The step-by-step motor is geared to its compass card so that the card moves 1 degree for each six steps of the motor.

There are two step-by-step systems in use, the only difference being the voltage supplied to the motor coils. The older system operates on 20 volts, the newer one on 70 volts.

A hand reset knob is provided on step-by-step repeaters, so that the motor can be turned by hand to agree with the reading on the master compass each time the power supply is recon-



gure 57-47 - Step-by-step system

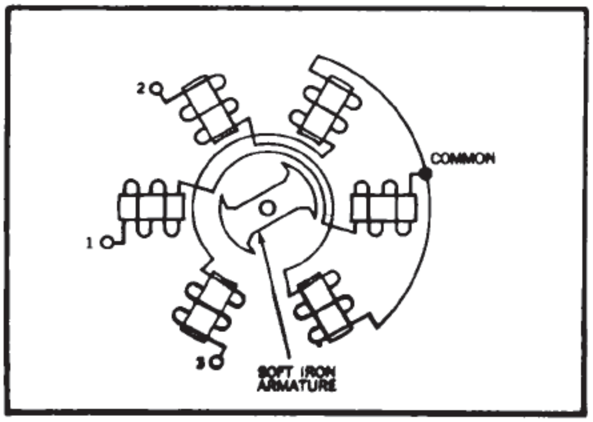


Figure 57-48 - Step-by-step motor.

nected. The reason for this is that there are two positions on the motor where the armature can lock in, giving 719 erroneous readings on the compass repeater

SERVOMECHANISMS

57-24. Purpose of Servos

The steering of a ship; positioning of a gun, missile launcher, or radar antenna, requires much more force than is developed by a synchro torque receiver or differential receiver such as described earlier in this chapter.

Some sort of output system is necessary to furnish the required power output with a variable speed and direction.

57-25. Description

A servomechanism is an electromechanical device that positions an object in accordance with a variable signal. The signal source may be capable of supplying only small amounts of power. A servomechanism operates to reduce difference (error) between two quantities. These quantities are usually the CONTROL DEVICE position and the LOAD position.

The essential components of a servomechanism system are the INPUT CONTROLLER AND OUTPUT CONTROLLER.

The input controller provides the means whereby the human operator may actuate or operate the remotely located load. This may be achieved either mechanically or electrically. Electrical means are most commonly used. Synchro systems are widely used for input control of servomechanism systems.

The output controller of a servomechanism system is the component or components in which power amplification and conversion occur. This

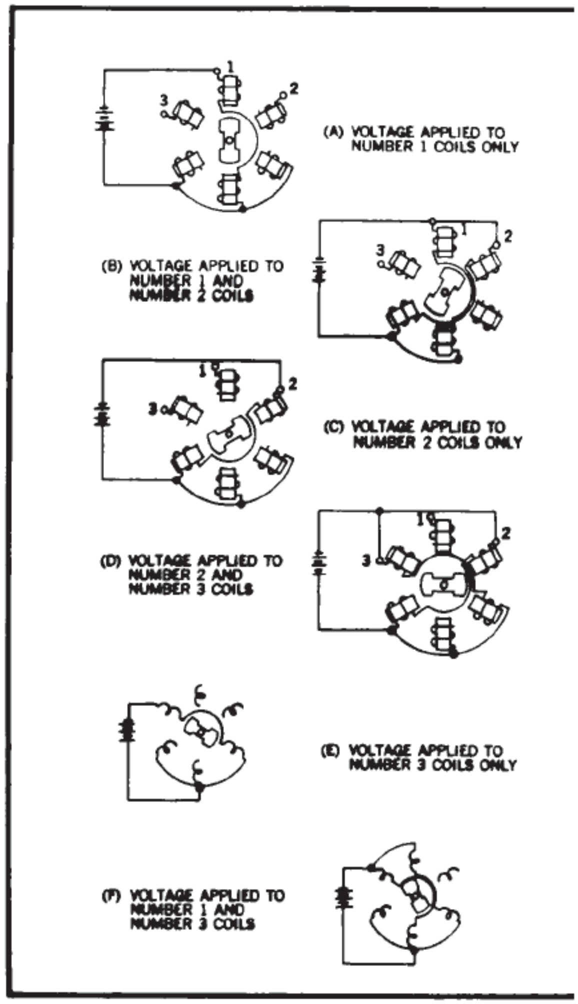


Figure 57-49 - Step-by-step motor operation sequence.

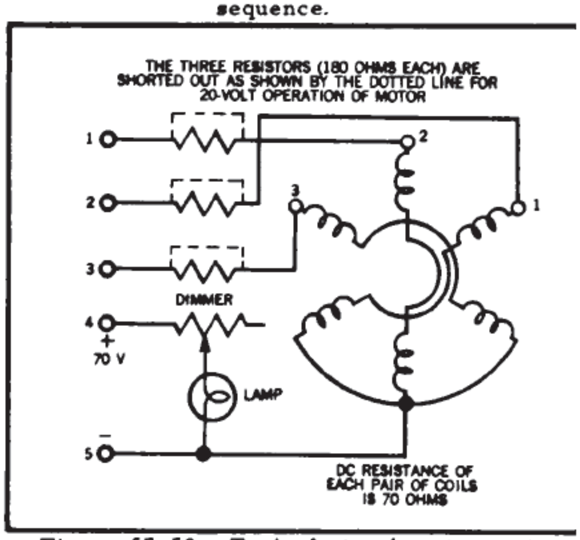


Figure 57-50 - Typical step-by-step motor showing terminals.

power is usually amplified by vacuum-tube amplifiers. In many applications a combination of these are used. The power from the amplifier is then converted by the servomotor into mechanical motion in the direction required to produce the desired function.

This sequence of functions is shown in Figure 57-51. The figure shows a simplified block diagram of a simple servomechanism system.

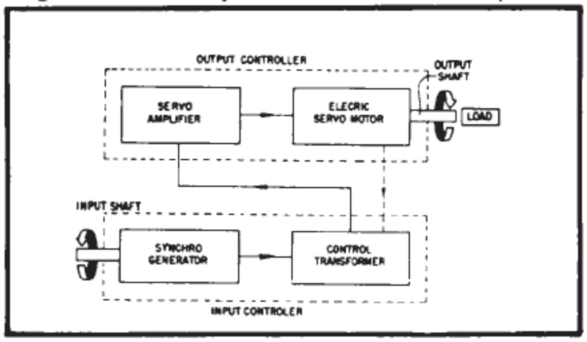


Figure 57-51 - Simplified block diagram of a servomechanism.

Q21. What are the essential components of a servomechanism?

57-26. Operation of Basic Servomechanism

There are two basic types of systems. They are: the open system and the closed system. It is not always easy to make a fundamental distinction between the two. An open system may be part of a larger system that is closed, or a closed system may be part of a larger system that is open. The basic distinction between the two lies in whether or not the action of the control is affected by the result of its earlier action. A system that operates only in response to external orders, independent of the result of its action, is an open system. A system that responds both to external orders and the action of the load or quantity that it controls is a closed system.

Figure 57-52 shows a schematic diagram of an open system. Note the absence of a mechanical response from the output controller to provide cancellation of the driving signal to the servomotor.

The input controller, which consists of a synchro control transmitter (CX) and a synchro controller transformer (CT), originates, or commands, the system movement. The CX's rotor is attached to a shaft, which is turned by hand or by a controlling mechanical device. Movement of the CX rotor from its electrical zero will cause an unbalance of voltages in the stator windings: S_1, S_2 and S_3.

A voltage is induced in the rotor of the

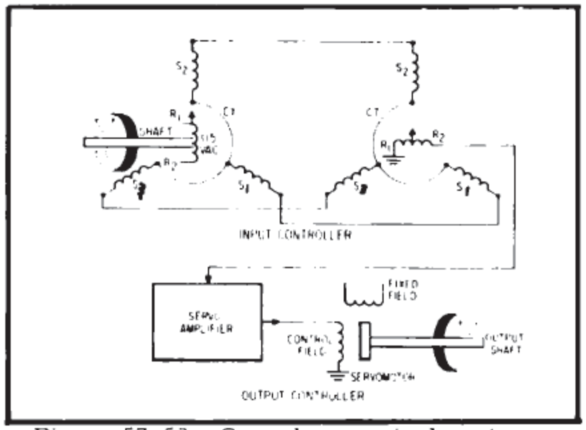


Figure 57-52 - Open-loop control system.

control transformer. Its magnitude depends on the amount of displacement of the CX rotor; its phase relationship depends on the direction of displacement from electrical zero. This voltage represents the error voltage. Since a control transformer is not designed to furnish enough power to drive a load of any significant size, the error voltage must be amplified before it is powerful enough to drive the servomotor, and thus move the load.

The output of the power amplifier is connected to the control field of the servomotor. In this illustration, a single-phase induction motor is used. The fixed field is energized only when an error voltage appears at the control transformer. When the control field is energized, the motor operates.

The direction of rotation of the motor is determined by the phase relationship of the voltage applied to the fixed field to that of the control field. Varying phase relationships occur in the control field only, because its voltage (magnitude and phase relationship) is determined by the direction of displacement of the control transmitter rotor.

Once the input controller in the system just discussed produces an error voltage, the servo motor continues to turn until the rotor of the control transmitter is again in its electrical zero position (null position).

Q22. What condition is necessary to cause a servo motor to operate?

Q23. How is an error detected and corrected in a servo system?

57-27. Ward-Leonard System

As previously stated, one of the basic requirements of a servomechanism is that the drive motor possess variable speed and reversi-

ble rotation capabilities. Since the ordinary single-phase or three-phase ac motor is inherently a constant-speed device, the direct current motor is commonly used for controlled drives. The direction of rotation can be changed readily by reversing either the armature current or the field current.

The speed can be controlled by the voltage on the armature.

The circuit shown in Figure 57-53, commonly known as the WARD-LEONARD system, accomplishes this result. The dc motor in this circuit is fed directly from a dc generator which is operated at a constant speed. The dc field supply to the generator is variable in both magnitude and polarity by means of a rheostat and

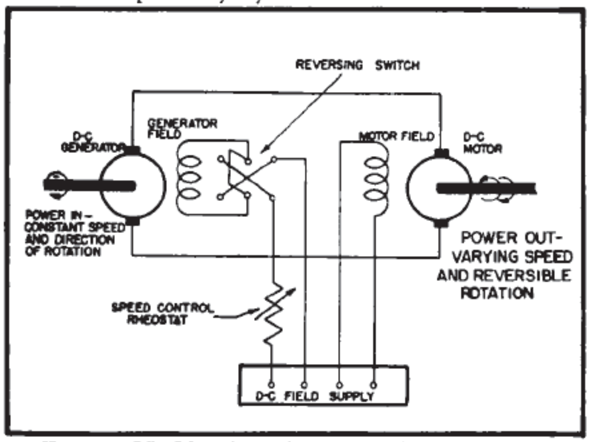


Figure 57-53 - Ward-Leonard drive.

reversing switch as shown. Therefore, the motor armature is supplied by a generator having smoothly varying voltage output from zero to full-load value. The motor field is supplied with a constant voltage from the same source as that supplying the generator fields. The generator drive power could be from a single-phase or three-phase ac motor, from an engine, or from any other constant speed source. In the same way the dc field supply can be supplied from a rectifier, from an exciter on the end of the generator shaft, or from any other suitable dc source.

Q24. What determines the direction and speed of rotation of the dc drive motor of a Ward-Leonard type of servomechanism?

Q25. What type of excitation is supplied to the drive motor field of a Ward-Leonard servo drive?

The advantage of the Ward-Leonard system is that by means of the variation of a small field current, a smooth, flexible, yet stable control can be maintained over the speed and direction of rotation of a dc motor. Such systems are applicable to ship propulsion, hoists and elevators, diesel electric equipment and to the rotation of gun turrets, radar antennas, and similar heavy equipment. The action of the

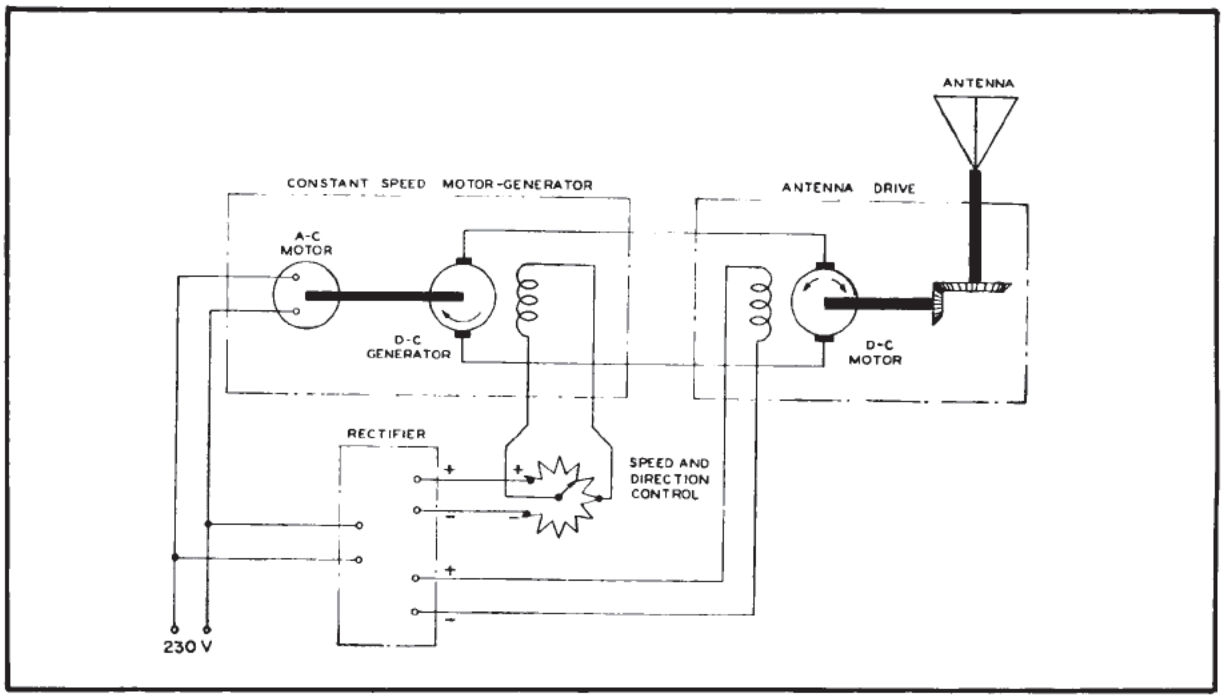


Figure 57-54 - Simple radar antenna drive.

A21. The essential components of a servomechanism are the input controller and the output controller.

A22. A servo system will operate only when an error exists in the system.

A23. In a servo system, an input quantity is compared with an output quantity and the difference, if any, is converted into an error signal which controls the positioning of the load until the error is reduced to zero.

A24. The direction and speed of rotation of the dc drive motor of a Ward-Leonard type servomechanism is determined by the output of a constant speed dc generator whose excitation is a variable dc voltage supplied by the input control device.

A25. The drive motor field of a Ward-Leonard servo drive is supplied with a constant voltage from the same source as that supplying the generator fields.

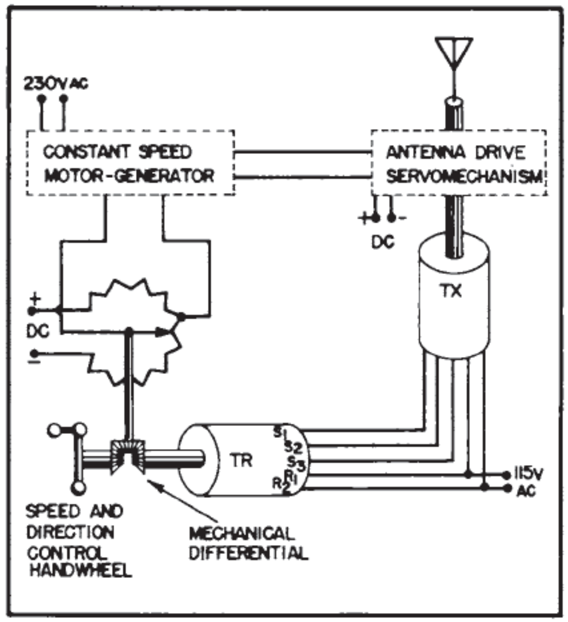


Figure 57-55 - A Feedback system for Ward-Leonard type servo control.

system is very much like that of an amplifier since a very small amount of power is used to control greatly increased power.

A simple Ward-Leonard drive for a radar antenna is shown in Figure 57-54. The dc generator in this system is driven by a 230 volt single-phase ac motor. The same ac line supplies a rectifier which furnishes field supply for both the dc generator and the dc motor fields. However, the generator field is connected to a potentiometer in such a way that the magnitude and polarity of the applied voltage can be varied. By varying the setting of the potentiometer control knob, the antenna can be rotated in either direction and at any speed from zero to full rate.

The system shown is an open-loop type and is applicable to a search type radar where the speed and direction of the antenna rotation is under direct control of the operator. This system could be modified for use as a closed-loop system by providing feedback from the antenna drive mechanism to the speed and direction control potentiometer so that the voltage supplied to the field of the dc generator would be reduced to zero when the antenna position was in correspondence with the input order. One method of providing feedback for the system shown in Figure 57-54 is by use of a simple transmitter-receiver system and a mechanical differential, illustrated in Figure 57-55.

57-28. Amplidyne

The amplidyne drive is similar to the Ward-Leonard drive except that a special dc generator called an AMPLIDYNE is used in place of the regular dc generator. The principle difference between the amplidyne and the ordinary generator is that the field of the amplidyne requires a much smaller amount of control power for the same values of output power. In other words, the amplidyne functions as an electromechanical power amplifier in which the amplification is very much greater than in the Ward-Leonard generator.

An ordinary generator can be regarded as a one-stage amplifier as shown in Figure 57-56A, in which a small power input to the field controls a large power at the output terminals. The additional power supplied to the generator shaft by an engine or motor in this case corresponds to the power supplied to the plate of a vacuum-tube amplifier. In order to increase the amplification the output of one generator may be used to supply the control field of a second machine, as in Figure 57-56B. This arrangement acts, in effect, as a second stage of amplification and the total power gain of the system is the gain of the first stage multiplied by that of the second. However, instead of having two separate armatures, the amplidyne has been designed to incorporate both stages of amplifi-

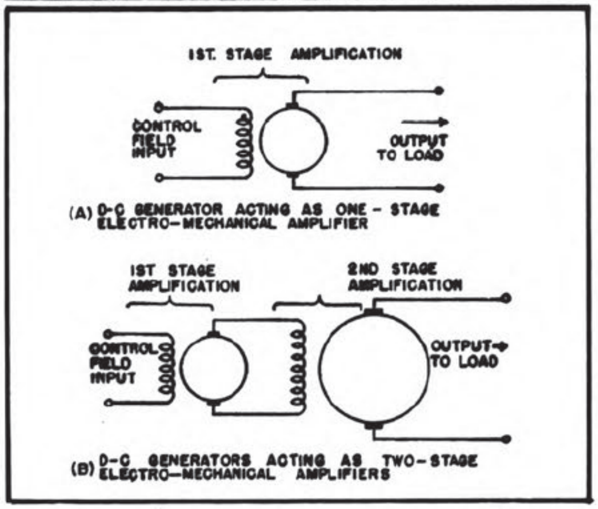


Figure 57-56 - Generators as electromechanical amplifiers.

cation into one armature.

Figure 57-57 shows the magnetic fields in a conventional dc generator supplying a load current of 100 amperes. The field current required to create the necessary excitation flux may be in the neighborhood of 5 amperes. Because of this flux, labeled ϕ_e in the drawings, there is a north pole in the machine frame at the left and a south pole in the frame at the right. Since the armature current of 100 amperes also flows through turns of wire on an iron core, the armature itself becomes an electromagnet. Magnetic flux generated in this manner is termed armature reaction flux and is shown in Figure 57-57A by the flux loops labeled ϕ_a. If the direction of the current in the armature conductors is considered, it is evident that the armature reaction flux is at right angles to the excitation flux as in Figure 57-57B.

If the external load is removed from the armature circuit and a short circuit is connected across the brushes, the excitation or control field current must be reduced greatly to prevent damage to the generator because of excessive armature current. The only resistance in the armature circuit in this case is that of the armature conductors, of the brushes, and of the short-circuit connection. Therefore, only a very small voltage need be induced in the armature to produce 100 amperes in the armature circuit, and the control field current must be reduced from 5 amperes to perhaps as low as 1/20 ampere.

Figure 57-58A shows the magnetic fields set up in a short-circuited dc generator. If the armature current is limited to 100 amperes by

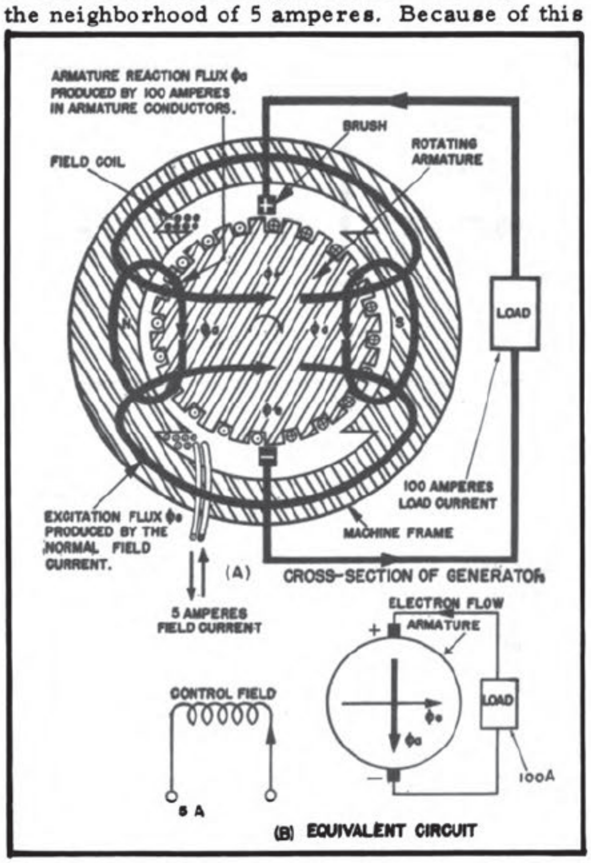


Figure 57-57 - Magnetic fields in conventional dc generator.

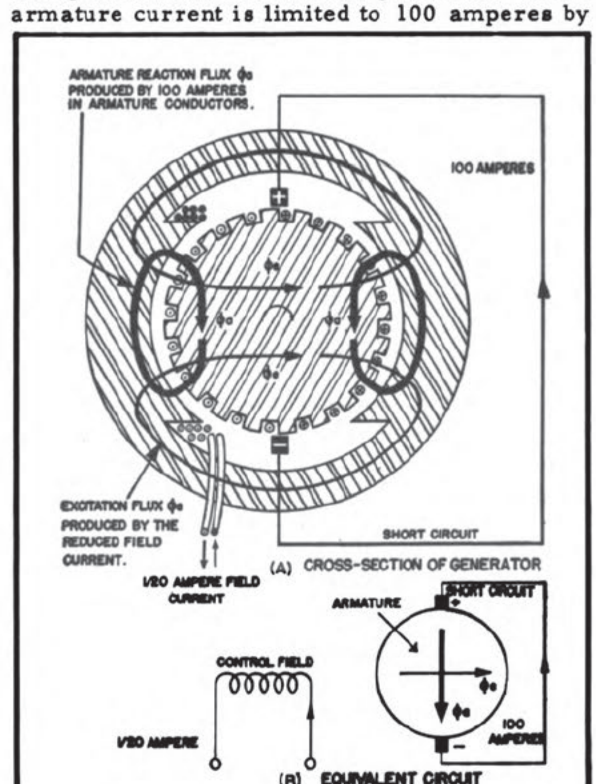


Figure 57-58 - Magnetic fields in short-circuited dc generator.

reducing the control field, the magnitude and direction of the armature reaction flux are the same as in the loaded generator of Figure 57-57, but the control flux is very small. The currents that flow in the armature conductors because of the short circuit are such that the armature reaction flux remains fixed in space, just as though the armature were a stationary coil with its axis at right angles to the axis of the control field windings.

Since the armature conductors are uniformly distributed about the armature, it is evident that some of these conductors will cut across the reaction flux at the same rate as others cut across the excitation flux. However, because of the location and direction of the two magnetic fields, the maximum voltage caused by the cutting of the reaction flux appears across the armature at right angles to the voltage developed by the excitation flux. Therefore by placing a second set of brushes at right angles to the short circuited brushes, shown in Figure 57-59, sufficient voltage is available to supply another 100 amperes to an external load, in addition to the 100 amperes flowing through the short-circuited path. Since the control field flux has to build up only to a low value and since the resistance of the short-circuited armature is very small, full load current may be obtained in an exceptionally short time. Thus, changes in the control-field are amplified almost instantaneously by the amplidyne.

However, the direction of the load current is such that it produces a second armature reaction flux (ϕ_b in Figure 57-59) which is at right angles to the short-circiut armature reaction flux ϕ_a, and in direct opposition to the original control flux, ϕ_e. The load armature reaction flux will be much greater than the control flux, and would prevent the control field from controlling the output. It is very important that the small control flux not be affected by the armature reaction if it is to retain control over the output. Therefore a series compensating winding through which the load current flows is wound around the control-field poles. The number of turns in this winding usually is adjusted so that the

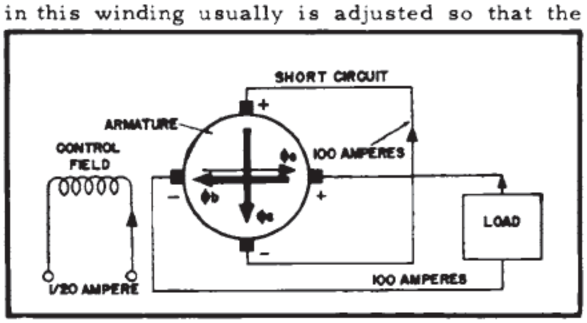


Figure 57-59 - Addition of second pair of brushes to short-circuit dc generator.

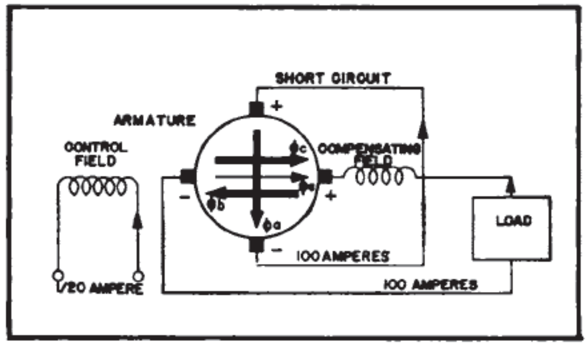


Figure 57-60 - Addition of compensating winding to short-circuited dc generator.

compensating flux (ϕ_c in Figure 57-60) exactly cancels the load armature reaction flux for all values of load current in the operating range.

In this case, the effective magnetic fields are as shown in Figure 57-61. If the compensating flux is slightly under the value for complete neutralization, the machine has reduced power gain and acts as a degenerative amplifier; however, the operation may be somewhat more stable. Overcompensation, on the other hand, creates the effect of regenerative amplification, and the operation of the machine may easily become unstable.

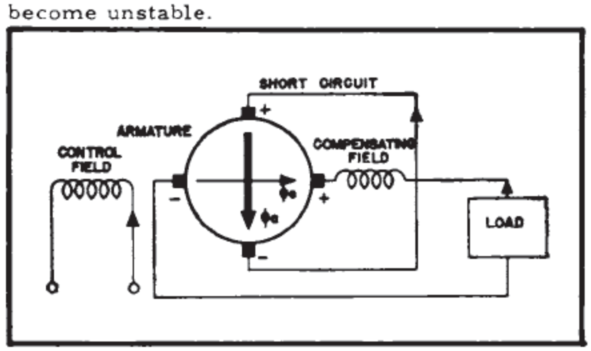


Figure 57-61 - Effective magnetic fields in amplidyne.

Since any residual magnetism along the axis of the control field would have a large effect on the amplidyne output, it is necessary to demagnetize the core material. This demagnetization is accomplished by attaching an Alnico magnet on the end of the armature. The magnet revolves within the separate field winding and generates a small ac voltage which is applied to two sets of opposed windings, called KILLER WINDINGS, on the field poles as shown in Figure 57-62. Thus the generated alternating current neutralizes any residual magnetism when the control-field current is zero. The effect of this demagnetizing system is similar to that created by an ac coil used to demagnetize watches.

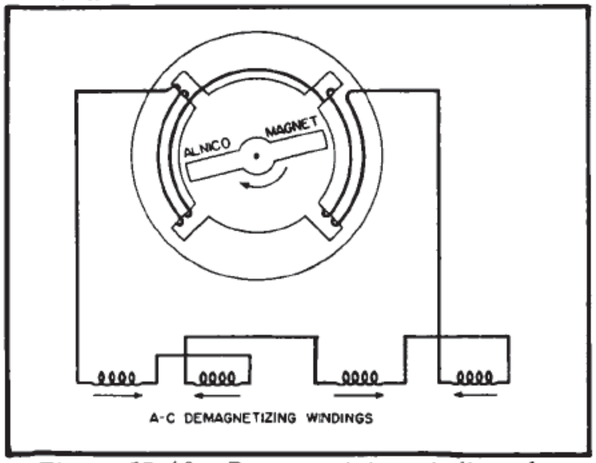


Figure 57-62 - Demagnetizing windings for amplidyne generator.

Returning to the diagram of Figure 57-56, it may be noted that the production of the short-circuit current and its associated armature reaction flux by a small control field represents the first stage of amplification, which can be regarded as principally current amplification. The use of this large current and the flux it produces to induce sufficient voltage to drive an equally large current through the external load circuit represents the second stage, which can be regarded as a feedback circuit, where exact compensation corresponds to zero feedback. The power gain of an amplidyne may range from 3,000 to 10,000 and perhaps higher in certain machines. This is in contrast to the gain of ordinary generators which will likely be in the range of 25 to 100.

Q26. What is the outstanding characteristic of the amplidyne system?

Q27. How many stages of amplification are accomplished in the amplidyne unit?

57-29. Control Amplifier

The amplidyne drive commonly used consists of the basic system as shown in Figure 57-63. Note that the symbol used for the amplidyne generator is similar to that of the conventional dc generator, except that an extra set of brushes connected by a curved shorting bar has been added. The amplidyne generator is ordinarily driven by an ac motor. The control field is shown as a split winding, as it is common to supply the fields by means of the CONTROL AMPLIFIER having separate outputs for each polarity of the signal applied. The series compensating winding is usually omitted from schematic drawings to avoid complication. The

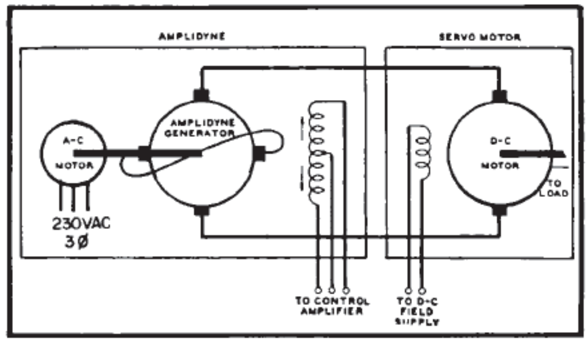


Figure 57-63 - Basic amplidyne drive.

field of the dc motor can be supplied by a rectifier or by a pair of permanent magnets. In motors having a permanent-magnet field the heavy armature current creates a large armature reaction flux which tends to demagnetize the permanent magnets. To prevent this demagnetization, compensating windings are connected in series with the armature and wound on the faces of the field poles to neutralize the armature reaction flux.

Figure 57-64 shows the basic type of control amplifier which is ordinarily used to supply the amplidyne control field. Such an amplifier is controlled by comparing an ac error voltage from a synchro control transformer to an ac reference voltage furnished by the ac line supply. Actually the 115 volt, 60 cycle, ac line supplies both of the transformer inputs, but the error voltage input to T_1 may be varied in magnitude or reversed in phase with respect to the reference voltage input of T_2 by means of the synchro transformer. The polarity signs are shown for a particular instant. It is assumed that there is no phase-shift and therefore both ac input voltages are in phase. The plates of both tubes are positive, but the grid of V_2 is below cut off,

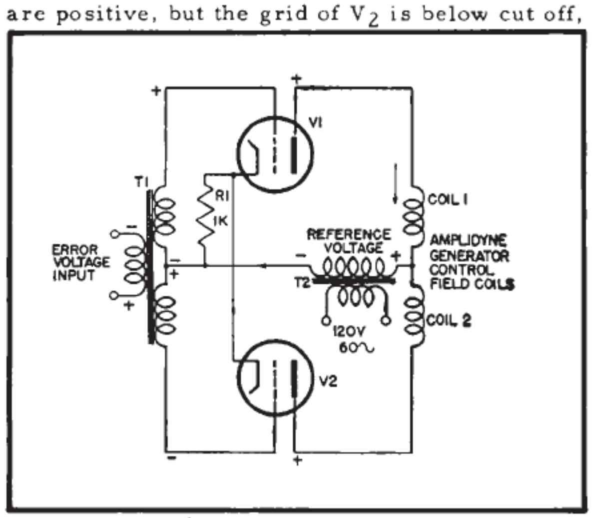


Figure 57-64 - Basic amplidyne control transformer.

A26. The amplidyne is best known for its unusual performance as a power amplifier.

A27. The amplidyne accomplishes two stages of amplification.

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and the grid of V_1 is above cut off. Therefore, electron flow is as shown by the arrows from V_1, and the field coil 1 is energized. On the next half cycle the plates are both negative and no current flows regardless of the grid voltages, which have also reversed. Thus the output is that of a half-wave rectifier supplying coil 1; coil 2 is inoperative.

If the phase of the voltage input to grid transformer T_1 is shifted 180° (reversed) while the phase of the ac line input remains the same as before, the circuit acts as a half-wave rectifier for coil 2, and coil 1 is inoperative. If the two coils are both wound on the amplidyne field poles, but in opposite directions, a 180° shift in ac grid voltage changes the direction of the control field flux and hence changes the polarity of the amplidyne output. The magnitude of the amplidyne output is thus controlled by the magnitude of the ac error voltage, and the polarity by the phase of the error voltage.

The basic amplidyne drive, as shown in Figure 57-63, may be applied to a servo system as shown in Figure 57-65. To illustrate the action of the control amplifier, assume that the handwheel is turned through some angle. The rotor of the synchro transformer, TX_1, includes in the stator winding a new direction of field which is transmitted to the stator winding of synchro control transformer CT_1. The rotor winding of CT_1 which has been in a position of zero induced voltage now develops an error voltage which is fed to the control amplifier input. Depending upon the direction the handwheel is rotated, the voltage is either in phase or 180° out of phase with the 115 volt ac line voltage. For the purpose of describing the control action, an in phase condition will be assumed as shown by the small sine waves of input voltage in Figure 57-65.

A positive half-cycle of the voltage from the rotor applied to transformer T_1 causes point A to be positive while point B is negative. Hence the grid of V_1 is positive while the grid of V_2 is negative. During the same time, a positive half-cycle is applied to transformer T_2 causing points C and D to be positive with respect to ground, so that the plates of both V_1 and V_2 are positive and the tubes conduct according to the grid voltages. Thus, V_1 conducts more heavily than V_2. The increased IR drop through R_6 charges capacitor C_1 with a polarity as shown in Figure 57-65. During this same positive half-cycle, tubes V_3 and V_4 remain inoperative because the cathodes are positive relative to the plates.

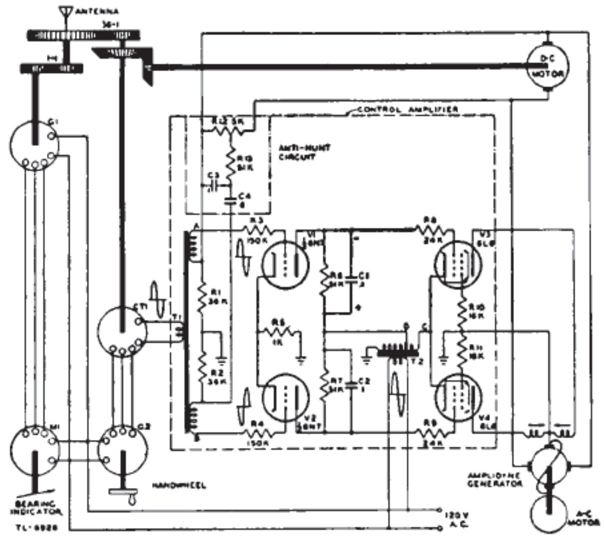

Figure 57-65 - Amplidyne servo system.

On the following negative half-cycle the grids of V_1 and V_2 interchange polarity, but since point D on transformer T_2 is now negative, V_1 and V_2 have a negative voltage on their plates and cannot conduct. Due to the reversed polarity on T_2 the plates of V_3 and V_4 are positive and these tubes can conduct if their grid voltages are above cut off. The biases on the grids of V_3 and V_4 are produced by the combination of a positive voltage existing between C and D on the transformer winding in series with negative voltages caused by the changes on C_1 and C_2. Since C_1 has a greater change than C_2, the grid of V_3 is more negative than that of V_4. The result is that V_4 conducts more than V_3. Equal currents in the plate circuits of V_3 and V_4 would produce equal opposing fields in the amplidyne, as shown by the arrows and the resultant field would be zero. However, when V_4 conducts more heavily than V_3, there is a resultant field flux and the amplidyne furnishes power to the drive motor. To rotate the drive motor in the opposite direction, V_3 must conduct more than V_4. This condition is brought about by an input into T_1 inverted in phase from the input assumed in the foregoing discussion.

Q28. What is the purpose of the compensating windings in the amplidyne generator?

57-30. Anti-Hunting

As soon as the drive motor has rotated the antenna so that the rotor winding of CT_1 is again at right angles to the stator field, the input voltage to T_1 is again zero and the drive motor stops. To prevent overshooting of this final antenna position, with its consequent HUNTING effects (oscillation), a feedback voltage is taken from the amplidyne output terminals and placed across the voltage divider R_{12}. A portion of this voltage is applied to resistors R_1 and R_2 in series by means of capacitor C_4. R_{13} and C_3 comprise a filter network to reduce generator ripple.

If, for example, the amplidyne voltage begins to build up as a result of an input voltage from the synchro rotor, C_4 starts to charge through R_1 and R_2. Since R_1 is in the grid-cathode circuit of V_1 and in series with the split secondary winding of the transformer, any voltage developed across R_1 appears as additional grid voltage on V_1. The same is true of R_2 with respect to V_2. The polarity of the feedback voltage is such as to aid the error voltage which is applied to the grids of the secondaries of T_1. The extra amplifier unbalance caused by the feedback voltage is small at the start, but the effect is cumulative. The faster the amplidyne voltage increases, the greater the unbalance becomes to cause even further increase in output. In this manner the antenna drive motor receives extra power to accelerate the antenna turntable.

The charge on C_4 reaches a maximum as the amplidyne output voltage levels off to a substanially constant value, and the feedback voltage drops to zero. As the antenna approaches the final position required by the field position of the synchro transmitter, the rotor of CT_1 supplies a diminishing voltage to T_1. As soon as this occurs capacitor C_4 begins to discharge through resistors R_1 and R_2, and voltages are produced across R_1 and R_2, which are the reverse of those present during the charging of C_4. The feedback now tends to offset rather than to aid the error voltage in the secondaries of T_1. The reversed feedback voltage resulting from the discharge of C_4 reduces the amplidyne output still further. Since the action is again cummulative, the result is a rapid decrease of amplidyne output. The overall action accomplished by the network consisting of R_{12}, C_4, R_1, and R_2 is called ANTI-HUNT; that is, the measures taken to prevent the antenna from oscillating around the point of synchronization (correspondence with the handwheel input).

With feedback potentiometer R_{12} properly adjusted, the output of the amplidyne falls to zero in time to compensate for the inertia of the driving motor and rotating antenna parts. In such case the antenna stops so that no error voltage is induced in the rotor of CT_1 to unbalance the amplifier further. If the amount of feedback, as determined by R_{12} is too great, the antenna stops too soon, with the rotor of CT_1 out of the zero voltage position. The drive motor then starts up rapidly and a condition for HIGH FREQUENCY hunting is established. On the other hand, insufficient feedback prevents the anti-hunt circuit from exerting enough effect to overcome inertia of the load, and the system will hunt at some LOW FREQUENCY. A condition of violent hunting can also arise if the feedback voltage is not of the proper polarity.

Q29. What is the purpose of an anti-hunt circuit in a servo control sytem?

57-31. Two-Phase Motor

The output drive motor in a servo system should be easily reversible and its speed should be variable over a fairly wide range. Ordinarily, an ac motor cannot fulfill these requirements completely because the range of speed control is limited. However, the use of an ac motor may provide a much simpler drive system, especially where an ac power source is available and where some sacrifice in range of speed control can be made.

An ac motor which can be adapted for servo-system use is the two-phase induction motor. This motor consists of two stator windings spaced 90° electrically from each other and either a wound rotor or a SQUIRREL CAGE rotor. The latter type of rotor is probably the most common. It consists of heavy conducting bars set into the armature slots and shorted by conducting rings at the ends. The schematic diagram for such a motor is shown in Figure 57-66. The voltages fed to the two stator windings must be 90° out of phase. This 90° phase difference plus the effect of the 90° mechanical spacing of the windings results in a rotating magnetic field. The rotating field induces a voltage in the rotor by transformer action, and hence the rotor is turned by the interaction of the magnetic fields present.

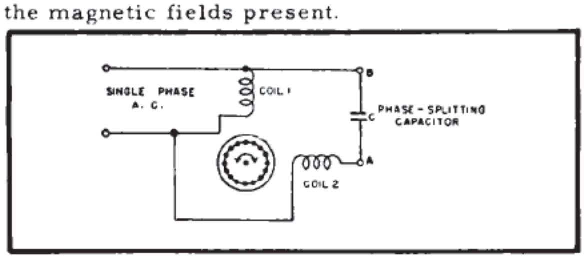

Figure 57-66 - Two-phase motor operating from single-phase supply.

A28. The purpose of the compensating windings in the amplidyne generator is to create a magnetomotive force to counterbalance the armature load current mmf.

A29. An anti-hunt circuit is used to prevent overshooting in a servomechanism without sacrificing accuracy and speed of response.

Since a two-phase ac supply is rarely available, it is customary to operate the two-phase motor by placing a PHASE-SPLITTING CAPACITOR in series with one of the stator coils. The current through this coil then leads the voltage by some angle less than 90°, while the current through the other coil lags by an angle less than 90° because of the impedance of the winding. If a capacitor of the proper size is chosen, the current in the two windings can be made to have nearly 90° phase difference, as required for the rotating field

Since the capacitors required for induction motor applications are large in size, an equivalent effect may be obtained by the use of a smaller, higher voltage capacitor and a small auto transformer. Figure 57-67 shows the circuit frequently used. The auto-transformer can be regarded as an impedance changing device which reduces the high reactance of a small capacitor between A and D to the lower reactance of a large capacitor between A and B. The output terminals of the auto-transformer and capacitor may be connected to points A and B in Figure 57-66 instead of the capacitor alone.

In order to give wider range of speed control and better torque characteristics for radar

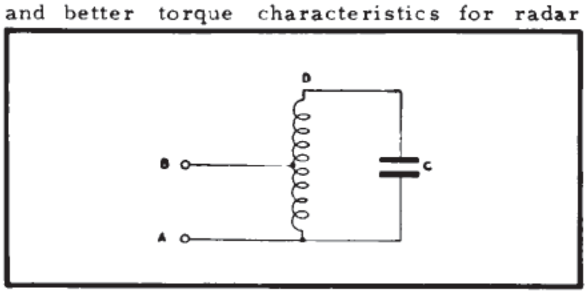

Figure 57-67 - Auto-transformer and capacitor used for phase splitting.

antenna-drive applications, it is possible to make certain other modifications of the two-phase motor. These include increasing the resistance of the rotor bars and use of the stator coil connections shown in Figure 57-68 to give more starting torque and greater rotor SLIP over the operating speed ranges. This diagram differs from that of Figure 57-67 in that the phase-splitting capacitor is placed in series with one coil, and the combination is placed in parallel with the second coil. The current through coil 1 is made up of the current that passes through coil 2 and capacitor C via the autotransformer. Since the current through the capacitor is leading the current through coil 2, the total current through coil 1 leads that through coil 2. The capacitor is chosen to give approximately a 90° phase shift between the current in coils 1 and 2. Thus, the desired rotating field is produced. A motor so connected tends to give a more constant current input over its speed range, and a much wider range in speed. The efficiency, however, is relatively poor.

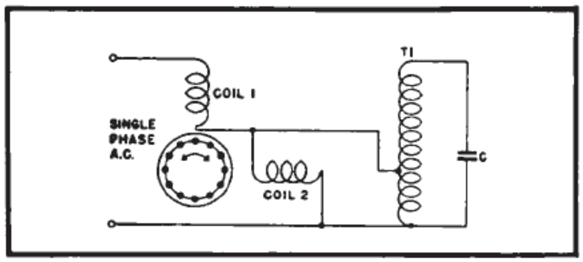

Figure 57-68 - Two-phase motor with series stator coil connections.

The direction of rotation of a two-phase motor is reversed either by reversing the connections to one stator coil or by shifting the capacitor from one stator coil to the other. The speed of the motor is varied over a limited range by changing the voltage applied to the motor. The voltage may be changed by placing a variable impedance in series with one or both phases. The effect of such an impedance is to lower the voltage, and hence the current, input to the windings without absorbing an excessive amount of power in the control device.

Q30. What is the phase relationship of the voltages used to drive a two-phase servo motor?

EXERCISE 57

1. What is a synchro?
2. What is a synchro transmitter, a receiver?
3. How do the synchro transmitter and receiver differ? How are they alike?
4. What is a torque transmitter?
5. What is the difference between 1-speed and 36-speed data transmission?
6. Describe the operation of a synchro network for one revolution of operation.
7. Describe briefly the troubleshooting procedure for synchros.
8. What is a differential synchro transmitter?
9. How is addition and subtraction accomplished with the TDX?
10. What is a control transformer?
11. What is the function of the synchro capacitor?
12. Why must synchros be zeroed?
13. How is zeroing accomplished with a voltmeter (CX or TX)?
14. What is a step-by-step synchro system?
15. What is a servomechanism, what is its function?
16. Describe the operation of a basic servomechanism.
17. Describe the operation of the Ward-Leonard system.
18. What is the outstanding advantage of the Ward-Leonard system?
19. What is an amplidyne, how does it operate?
20. What is the function of killer windings?
21. What is a control amplifier?
22. What is hunting?
23. What may be done to prevent hunting?
24. Describe the characteristics of a two-phase motor.
25. How may phase splitting be accomplished, why is it used?

A30. When a two-phase servomotor is used to position a load, the voltages supplying the two windings must be 90° out of phase.

CHAPTER 58

MAGNETIC AMPLIFIERS

The MAGNETIC AMPLIFIER is a device used to reproduce an applied signal at an increased amplitude. Although all amplifiers have this capability, the method by which this is accomplished is vastly different when a magnetic amplifier is used.

The vacuum tube circuit amplifies, because small changes in potential difference between grid and cathode produce relatively large changes in plate current, which in turn can be converted into large plate voltage changes.

The transistor circuit amplifies, because the input signal applied across the low resistance emitter-base junction controls the current through the high resistance collector-base junction.

It will be shown that the increases in magnitude that occur in the magnetic amplifier circuits are produced by the variations in magnetism and inductance within the unit.

Magnetic amplifiers are used as regulators, relays, amplifiers, motor starters, timing pulse generators, automatic stabilizers and automatic pilots for submarines and aircraft. They are also widely used in servo systems as converters and computers, and in many other applications.

The magnetic amplifier is known for its dependability, ruggedness, high efficiency and ability to withstand high temperatures.

Since a good knowledge of magnetism is essential to understanding the magnetic amplifier a brief review of basic magnetic theory will be given.

58-1. Elements of Magnetism

The principle of magnetism is used in a wide variety of applications, which include television, radio communications, automobiles and a host of other apparatuses. Without magnetism many of these conveniences would be non-existent.

Magnetism and electromagnetism, for many years were treated as two separate and distinct subjects. In the year 1821, Oersted noticed that a compass needle placed in the vicinity of a current-carrying wire would be deflected. Later Faraday and Henry showed that current could be induced into a conductor which was moved through a magnetic field; therefore, emphasizing the relationship between magnetism and electromagnetism. Thereafter, laws pertaining to magnetism were also applied to electromagnetism.

It should be recalled from earlier chapters, that the region around a bar magnet wherein its influence can be felt is called a magnetic field. This magnetic field can be thought of as a pattern of lines arranged in an orderly fashion leaving the north pole and entering the south pole, as shown in Figure 58-1.

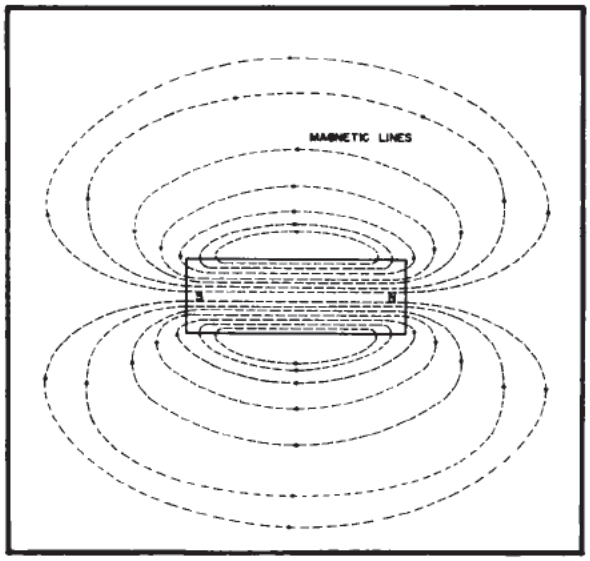

Figure 58-1 - Bar magnet and its magnetic field.

A similar pattern of magnetic field exists around a coil when current flows through that coil, as shown in Figure 58-2. The strength of the field is called MAGNETOMOTIVE FORCE (MMF), measured in gilberts, proportional to the ampere turns, as indicated by the formula:

$$MMF = 0.4\pi NI \text{ gilberts} \qquad (58\text{-}1)$$

where: MMF = the magnetomotive force in gilberts.

0.4π = a conversion factor (sometimes given as 1.257).

N = the number of turns in the coil

I = the current flowing through the coil

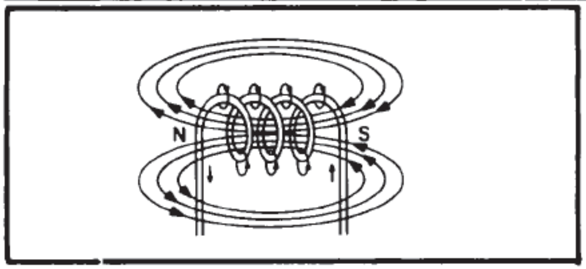

Figure 58-2 - Magnetic field about a current-carrying coil.

If a good understanding of magnetic circuits is to be achieved, other parameters must be considered. They are:

FIELD INTENSITY (H), sometimes called magnetic intensity is directly related to the magnetic force exerted by the field. The unit used in measuring field intensity is the oersted; one oersted being equal to the strength necessary to exert a force of one dyne per unit magnetic pole. This relationship may be expressed mathematically as:

$$H = \frac{f}{m} \qquad (3\text{-}3)$$

where: H = field intensity in oersteds
f = force acting upon a magnetic pole in dynes
m = strength of magnetic pole in unit poles

For a bar magnet or an electromagnet whose cross sectional area is small compared to its length, field intensity is directly proportional to the magnetomotive force and inversely proportional to the length of the magnet.

The formula then becomes:

$$H = \frac{MMF}{cm} = \frac{1.257\ NI}{cm} \qquad (58\text{-}2)$$

where: H = field intensity in oersteds
MMF = magnetomotive force in gilberts
cm = length in centimeters

MAGNETIC FLUX (Φ) is similar to current in an electric circuit and comprises the total number of lines of force existing in the magnetic circuit. The unit of flux is the MAXWELL. One line of force is equal to one maxwell.

FLUX DENSITY (B) is the means of measuring the amount of flux lines per unit area. In the CGS system, the GAUSS is the unit of measurement. The flux density is one gauss when there is one maxwell per square centimeter. Expressed as an equation:

$$B = \frac{\Phi}{A} \qquad (3\text{-}2)$$

where: B = flux density in gausses
Φ = flux in maxwells
A = area in square centimeters

PERMEABILITY (μ) is a comparative factor depicting the ease of which a material can conduct magnetic flux as compared to the ease of which a vacuum conducts flux. The formula for permeability is:

$$\mu = \frac{\Delta B}{\Delta H} \qquad (58\text{-}3)$$

where: μ = permeability
ΔB = the change in flux density
ΔH = the change in field intensity

It should be recalled that in a vacuum, flux density equals field intensity at all times and the μ of a vacuum is one. Materials with a permeability of less than one are called diamagnetic and those with μ slightly greater than one are called paramagnetic. Materials such as iron, cobalt and nickle have a μ much greater than one are referred to as ferromagnetic.

RELUCTANCE is the opposition to magnetic flux offered by a magnetic material. The equation for reluctance is:

$$R = \frac{cm}{\mu A} \qquad (58\text{-}4)$$

where: R = reluctance (sometimes the unit for R is the rel.
cm = length in centimeters
μ = permeability
A = area in square centimeters

Reluctance is equivalent to resistance in an electric circuit.

Rowlands law, which is similar to Ohm's law for electric circuits states that flux is directly proportional to MMF and inversely proportional to reluctance as indicated by the formula:

$$\Phi = \frac{MMF}{R} \qquad (58\text{-}5)$$

Therefore, an increase in MMF will result in a corresponding increase in flux, if R is constant. This will be true if a coil with an air

core is used, since the reluctance of air is always constant.

If iron is used as a core the flux lines find an easy path through it, since the reluctance of iron is very low.

It is more convenient to consider permeability when various types of cores are compared, because the ease in which μ can be plotted. Since μ is a ratio of flux density to field intensity, a B-H curve can be used to illustrate the effects of core material on μ. It was stated that the permeability of a vacuum is unity; however, the μ of air is only slightly greater than a vacuum and is frequently considered unity. Figure 58-3A shows the electromagnetic field around a coil with an air core. When an iron core is inserted in the coil as shown in Figure 58-3B the lines of force are concentrated and the flux density increases, due to the high permeability of iron.

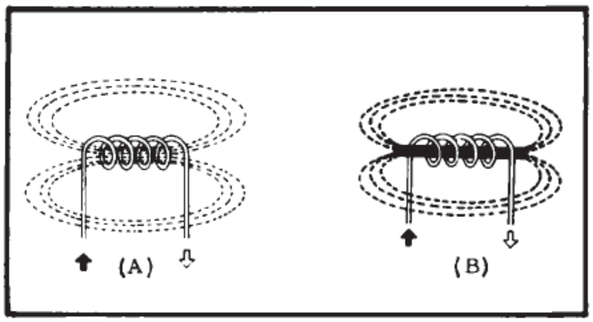

Figure 58-3 - Adding a core of magnetic material increases flux density.

Flux density is dependent upon the intensity of the field and the permeability of the core ($B = \mu H$). However, μ is independent of flux density and field intensity only when the ratio of B to H is constant.

If the current through the coil in Figure 58-3A were increased, the field intensity would likewise increase. The expanded field around the coil would result in an increased flux density. The core in this case is air and the flux density change is dependent only on the change in field intensity and the B to H ratio remains the same. Figure 58-4A is a plot of flux density against field intensity, when an air core coil is used. It shows that an increase in H, results in a linear increase in B.

An increase in current through the coil in Figure 58-3B would again result in an increase in field intensity; however, the core is now iron and variations in flux density are now greatly influenced by the ferromagnetic properties of the core. Figure 58-4B is also a plot of flux density against field intensity. The ratio of B to H is no longer constant, because increases in H no longer produce linear increases in B.

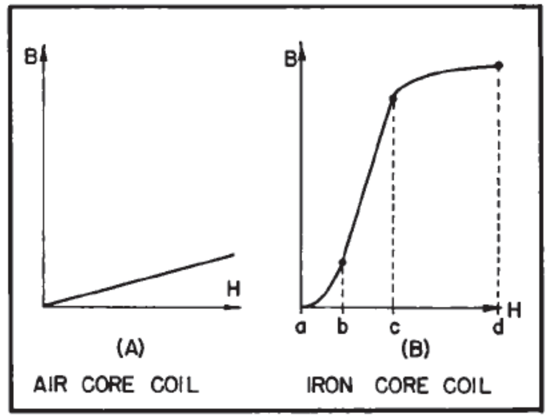

Figure 58-4 - Comparison of B-H curve of air coil to the B-H curve of an iron core coil.

When the field intensity is increased from point a to point b, the flux density experiences only a small increase and the permeability between these two points is low. This condition exists because most of the energy produced at this time is utilized in the initial alignment of the domains. An increase in H from point b to point c results in a drastic increase in B. The permeability at this time is very high. A further increase in H from point c to point d produces an insignificant change in flux density; this is true because saturation is reached at point c. Saturation in a ferromagnetic material is described as a condition when all the domains in the material are aligned and an increase in the magnetizing force cannot produce an increase in flux density. Point c is called the knee and it will be seen later that this section of the curve is very important in magnetic amplifiers.

Q1. What effect does the flow of current have on the permeability of an air core coil?

Q2. How may the permeability of iron core coil be varied?

58-2. Review of Inductance

It should be recalled from Chapter 9, that inductance is described as the property of an electrical circuit that opposes any change in current through that circuit. The effect of the various factors on inductance can be expressed by the following formula:

$$L = \frac{1.257 \mu A N^2}{l m \times 10^8} \qquad (9\text{-}4)$$

A1. No effect. The permeability of air is constant, since any change in H produces a proportional change in B.

A2. The μ may be varied by changes in the magnetizing force, for an example if the core is saturated an increase in H will not produce a proportional increase in B and μ will decrease.

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where: L = inductance in henrys
N = number of coil turns
10^8 = a constant used to convert L into practical units
μ = permeability of the core material
A = cross sectional area of core enclosed by one turn in sq. cm.
1.257 = a constant
lm = mean length of core in cm.

It is apparent that A, N and lm are factors that can only be varied physically. μ is a factor that depends upon the core material for its magnitude and its consistence. It has already been established that permeability is constant when the core is air, but can be varied in a ferromagnetic core. The inductance of a coil can therefore be changed whenever the core is iron or some other ferromagnetic material.

The opposition to the amount of change in current, offered by a coil (impedance) is proportional to its inductance. The impedance of a coil can therefore be controlled if the permeability of the core is controlled.

Q3. What are some of the factors that determine the amount of inductance of a coil?

Q4. What happens to L when the number of turns is increased?

53-3. Hysteresis

The discussion up to this point has been limited to electromagnetic circuits, having fixed or slowly changing direct currents and constant or slowly changing magnetomotive forces applied. Circuits having rapid changing MMF due to alternating currents will now be considered.

The word HYSTERESIS was derived from a Greek word meaning "to lag". Hysteresis, as it is applied to modern electronic terminology, is used to describe a general effect where the flux density lags the magnetizing force that produces it.

When an alternating current flows through an air-core coil, as shown in Figure 58-5, the flux density increases and decreases in phase with the force that produces it.

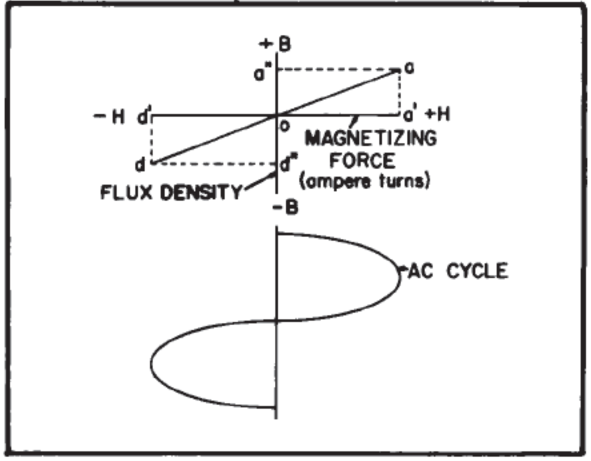

Figure 58-5 - B-H plot of alternating flux in an air core coil.

The B-H curve for an electromagnetic coil with a ferrous core is shown in Figure 58-6. As in the case of the air core coil, an alternating current is applied. Assuming that the alternating wave starts at 0 potential and increases in a positive direction, flux density will increase from point 0 to point a. It can be seen that although flux density increases at a non-linear rate, it is however in phase with the force that produces it (H). The magnetizing force reaches its maximum at point a and decreases until it reaches point 0 again. The flux density decreases along curve a-c; the rate of reduction in B is much slower than the rate of reduction in H. The force returns to zero, but the flux density only returns to point b, indicating that the core remains magnetized to some degree after the force has been removed. The remaining flux is called RESIDUAL MAGNETISM; the lag in flux is called hysteresis.

The ability of a core to remain magnetized after the force has been removed is called retentivity. The higher the retentivity the higher the residual magnetism.

When the magnetizing force is applied in the opposite direction, H must reach point c before the flux density returns to zero. The field intensity that is required to cancel the residual magnetism is called COERCIVE FORCE. The return of the force to zero again results in a reduction in flux, but as before B does not return to zero, but instead only proceeds to point e. A coercive force from point 0 to point f is needed ,to reduce the flux to zero. The flux is increased to point a, as H is increased to point a'.

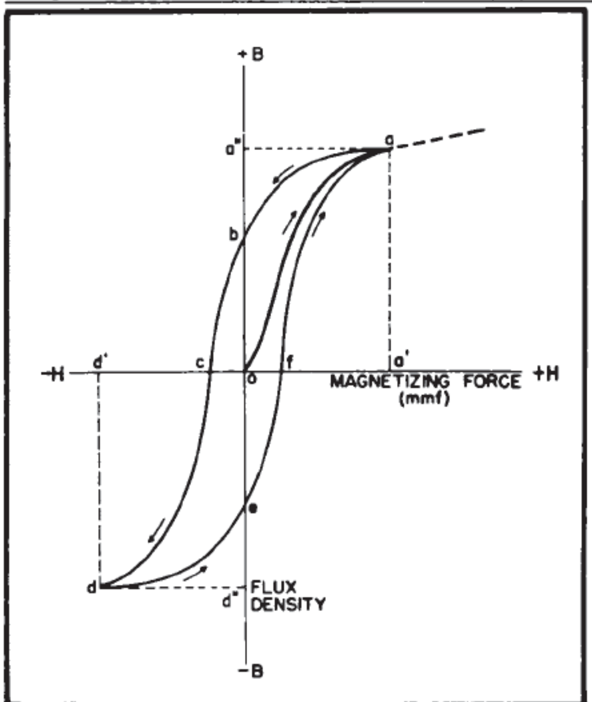

Figure 58-6 - B-H plot of alternating flux in iron core coil.

If the force is increased beyond point a', the flux density increases only slightly as indicated by the dotted line, since B has reached saturation. The permeability (μ) is very low at this time. The inductance of the coil is also very low at this time.

$$L = \frac{1.257\mu AN^2}{\text{length} \times 10^8} \qquad (9\text{-}4)$$

It should be recalled that the impedance of a coil, usually referred to as inductive reactance (X_L) is proportional to the inductance; with a sine wave applied the formula of inductive reactance is:

$$X_L = 2\pi f L \qquad (9\text{-}26)$$

The impedance of a coil with a ferrous core, is very low when the core is saturated and the impedance is very high during any time when flux density changes readily respond to field intensity change.

The plotted cycle of magnetization, a b c d e f a, is called the hysteresis loop.

Q5. Can it ever be said that the amount of current flow determines X_L? If so under what conditions?

58-4. Losses in an Iron Core Coil

The principle losses that occur in iron core coils are: copper losses, hysteresis loss and eddy current losses.

Copper losses are the same as those that occur in any current carrying circuit; since no conductor has a resistance of zero, the flow of current produces I^2R losses.

Hysteresis losses occur as a result of the lag in flux density when a magnetizing force is applied. Energy is lost because a portion of the force is utilized in overcoming the residual magnetism. The amount of hysteresis losses depends on several factors, among them are the type of core used, the temperature of the core and the frequency of the applied magnetizing force.

The type of the core will determine the ease or difficulty of which the magnetizing force overcomes the residual magnetism. Figure 58-7 is a comparison between the hysteresis loop of a core with high retentivity (A); one with medium retentivity (B), and one with low retentivity (C).

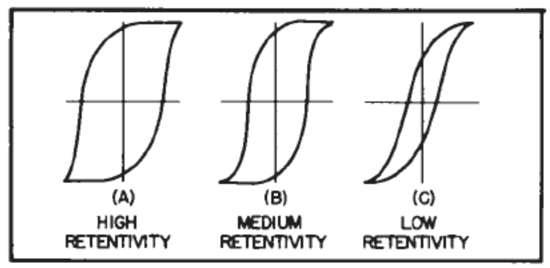

Figure 58-7 - Comparison of hysteresis loops of cores with different retentivity.

A core with a high retentivity has a wide hysteresis loop. The use of such a core results in high hysteresis losses. Whereas the use of a core with low retentivity, has a narrow loop and a small amount of hysteresis losses.

The temperature of the coil will to some degree determine the retentivity of a core. At high temperatures, the domains are easier to orient and the hysteresis losses are reduced.

When a slowly varying magnetizing force is applied to a coil having a ferromagnetic core, a static hysteresis loop is formed. If a rapidly changing force is applied, the B-H curve formed is called a dynamic hysteresis loop, and the amount of lag increases. The higher the frequency, the greater the lag and the wider the hysteresis loop. Since losses increase as the loop widens, the use of coils with ferromagnetic cores becomes impractical when high frequency signals are used.

Other important losses encountered in the ferromagnetic core are referred to as eddy

A3. The number of turns contained in a coil, length and cross sectional area of a coil and the permeability of the core used.

A4. L increase by a value equal to the square of the amount of increase in turns.

A5. Yes. When an iron core coil is used the μ may be varied by changing the magnetizing force. The magnetizing force is directly proportional to the ampere turns. Since any change in μ produces a proportional change in L and $X_L = 2\pi f L$, an increase or decrease in the amount of current can produce changes in X_L.

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current losses. The expanding and collapsing fields around the coil induce voltages into the core; since the core is made of conductive material, currents circulate within the core. If the core is solid as shown in Figure 58-8A, its resistance is very low; the current flow within the core will be high and the power loss will be great. If the core is laminated as shown in Figure 58-8B the resistance of the core will be increased and eddy currents will be reduced. The power loss therefore will also be reduced.

Eddy current losses must also be considered a limiting factor on frequency, since induced electromotive forces become excessive when high frequencies are applied. Although the resistance of the core is greatly increased by laminations, the power loss with such high induced voltages will be significant.

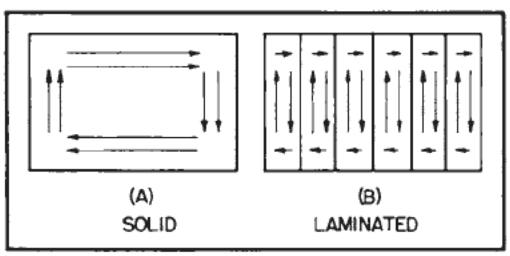

Figure 58-8 - Eddy currents, ferromagnetic cores.

All the above types of losses are dissipated as heat. The energy that is radiated in the form of heat reduces the efficiency of the circuit.

Q6. How does the applied frequency effect the width of the hysteresis loop?

Q7. Why is the width of the loop important?

58-5. The Saturable Reactor

The terms MAGNETIC AMPLIFIER and SATURABLE REACTOR are frequently used interchangeably. This, however, is erroneous since a magnetic amplifier is a device consisting of a combination of saturable reactors, resistors, rectifiers and conventional transformers which is used for control or amplification.

Although the saturable reactor is the main component in all magnetic amplifiers, this term (saturable reactor) applies to the reactor alone.

The principle of amplification is that a comparatively low-level signal controls relatively large amounts of power. In the saturable reactor a control signal does this by determining the permeability of the core. It has already been explained that a change in μ will change the inductance and therefore vary the inductive reactance (X_L) of the coil. Under most conditions the dc resistance of a coil is small in comparison to its inductive reactance; therefore the impedance offered by the coil to the change in current is mostly equal to its X_L.

It has also been explained that when a core is saturated its μ is extremely low and the impedance of the coil approaches a value equal its dc resistance.

A ideal saturable reactor core would have a B-H curve as shown in Figure 58-9A. Although no materials exist which have ideal characteristics, many materials approach the ideal curve. Part B of Figure 58-9 makes a comparison between the hysteresis loop for a transformer and one for a magnetic amplifier.

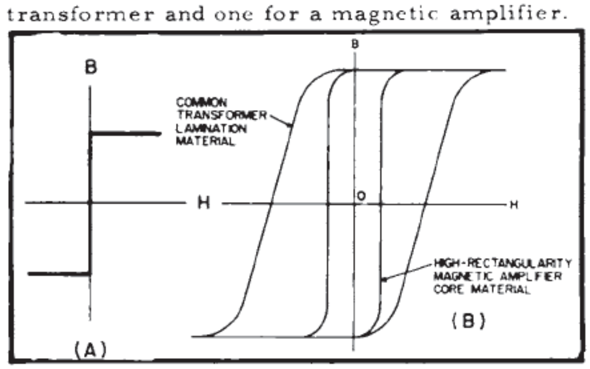

Figure 58-9A - Ideal and typical curves of magnetic core materials.

The impedance of a reactor load winding is controlled by controlling the amount of time in a given cycle during which the core is saturated and maximum load current is allowed to flow. Thus in the basic half-wave magnetic circuit shown in Figure 58-9B, assuming a sine wave input, if the control current is zero, only a slight voltage will be developed across the load as indicated by waveform (b). When the control current is equal to one-half its maximum value, the voltage across the load will assume the shape shown in waveform (c). When the control current is at it's maximum value, the voltage across the load will assume the shape shown in waveform (d).

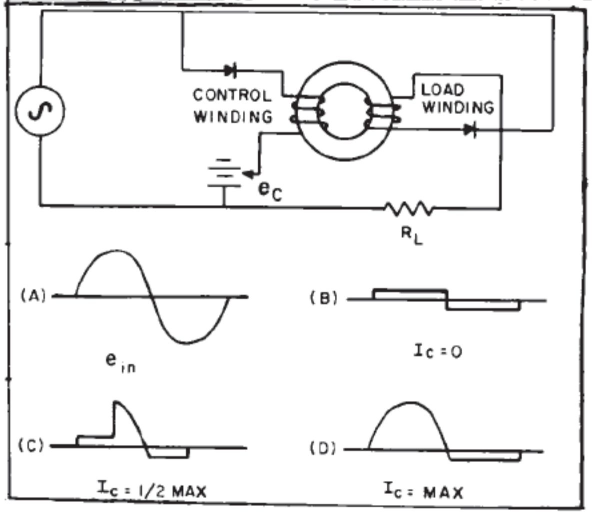

Figure 58-9B- Basic halfwave magnetic circuit and waveforms

The characteristics of an ideal magnetic core material should include:

1. Minimum hysteresis and eddy current losses.
2. High saturation flux density; that is, when the core has become saturated, it has a maximum number of lines of flux. This allows a given mass of core material to have a large power capacity. Note that this characteristic is not necessarily the same as high permeability.
3. High permeability. This provides a narrow hysteresis loop with steep sides so that a small value of magnetizing force will produce saturation.
4. Stable magnetic characteristics. Core characteristics should be relatively unaffected by temperature changes, mechanical strain and shock, and previous magnetization.

As iron is made more pure, its permeability increases. With sufficient purity, permeability above 300,000 have been achieved. In its pure state, iron has the highest permeability of all the elements; however, other useful characteristics can be achieved through the addition of certain controlled impurities. The addition of a small amount of silicon results in a relatively soft alloy with high resistivity. Such an alloy finds practical use in rotating armatures and as the core of power transformers. Where faithful reproduction of a waveform is required by a transformer, the core is generally made of a nickel-iron alloy which provides a relatively linear relationship between B and H. This results in a fairly constant permeability over a wide range of the B-H curve. Most saturable reactor cores are constructed of nickel-iron alloys. These materials are subdivided into the (1) high-permeability alloys, and (2) grain-oriented alloys.

High-permeability materials, such as permalloy A, Mumetal and 1040 alloy have low and intermediate values of saturation flux density but relatively narrow and steep hysteresis loops. These materials are used extensively as the cores in low-level input amplifier stages.

Grain-oriented materials, such as Orthonol, Deltamax, and Permeron have higher values of saturation flux density and more rectangular-shaped hysteresis loops than the high-permeability materials. Grain-oriented materials are referred to as square-loop materials due to the shape of their hysteresis loop as shown in Figure 58-9B. These materials are used as the cores of high-level output amplifier stages in which maximum permeability occurs close to saturation. This results in a substantial increase in the power-handling capability for a given weight of core material.

Two desirable characteristics in the construction of saturable reactor cores are (1) very thin laminations for reduced eddy currents and (2) gapless construction, a method of constructing the core to minimize flux leakage. Torodial or circular cores have much less flux leakage than rectangular cores. Flux lines follow curved paths and are not adapted to turning sharp corners. Thus rectangular cores have more flux leakage than toroidal cores as shown in Figure 58-10.

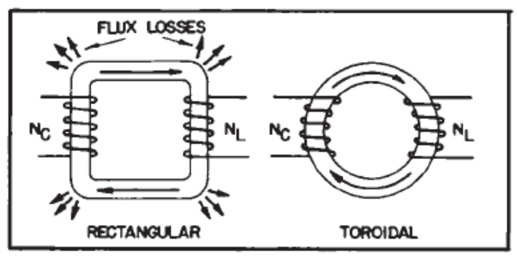

Figure 58-10 - Rectangular core as compared to toroidal core.

The flux produced when current flows through the dc control winding is not completely confined to the core. Some flux lines flow outside the core or through the insulating material on which the core is wound as illustrated in Figure

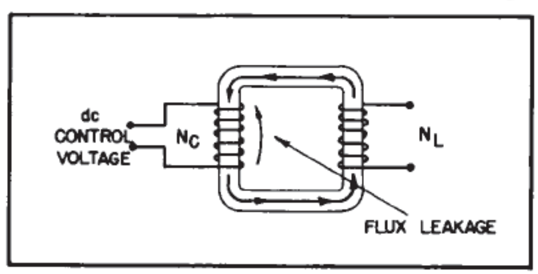

Figure 58-11 - Magnetic leakage in a saturable reactor.

A6. The frequency of the applied wave greatly determines the amount of lag, which in turn determines the width of the loop.

A7. The width is important because it shows graphically the amount of lag and hence the amount of losses in the core of a coil.

Therefore, the entire flux produced by the current in N_C does not pass through N_L. The amount of leakage will increase as core saturation is approached. This leakage is minimized in single core devices by winding N_C and N_L on the same leg of the core as shown in Figure 58-12. However, a great amount of insulation is needed to prevent arcing between N_C and N_L in Figure 58-12.

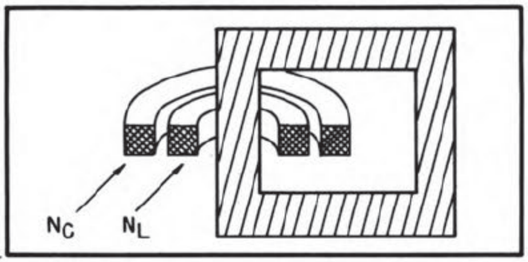

Figure 58-12 - Methods of reducing leakage flux.

Some reactors use two cores. They would also have N_C and N_L wound on the same leg to reduce flux leakage as shown in Figure 58-13. Once again a high amount of insulation would be needed between NC and N_L.

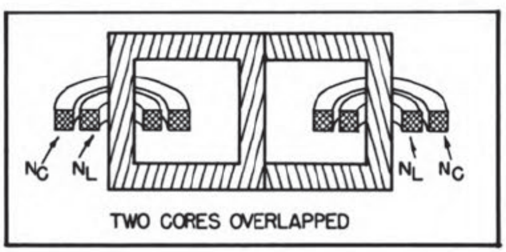

Figure 58-13 - Methods of reducing flux leakage in a two core reactor.

Another core called the three-legged core is often used and requires little insulation because the load and control windings are not wound on the same leg. It has less flux leakage than the core in Figure 58-11, but the flux leakage is not reduced as well as in Figure 58-12. The three-legged core in Figure 58-14 has the control winding wound on the center leg and one load winding on each outside leg.

Reactors, whether they have a single core, double core or three-legged core are classified according to their construction as follows:

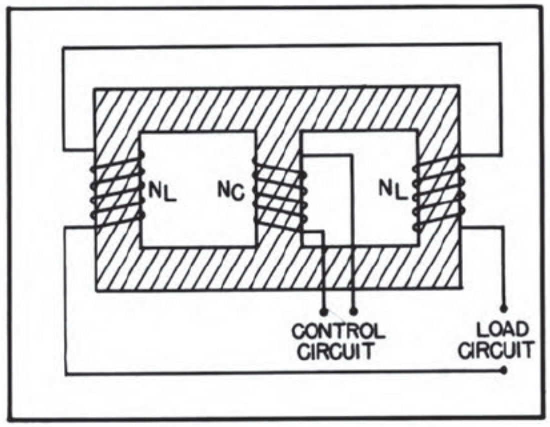

Figure 58-14 - Three-legged saturable reactor core.

1. Rectangular cores
   (a) stacked
   (b) spiral or tape wound
2. Toroidal cores
   (a) stacked
   (b) spiral or tape wound

The toroidal cores are more common than rectangular cores. Stacked and spiral cores are shown in Figure 58-15.

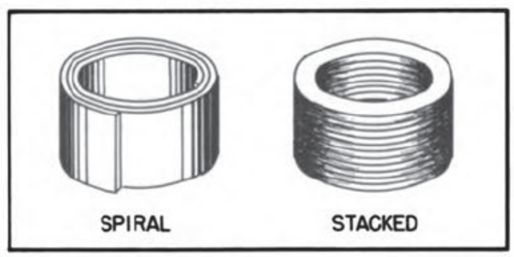

Figure 58-15 - Spiral and stacked cores.

Schematic representation of single ring, twin-ring and three-legged cores is shown in Figure 58-16.

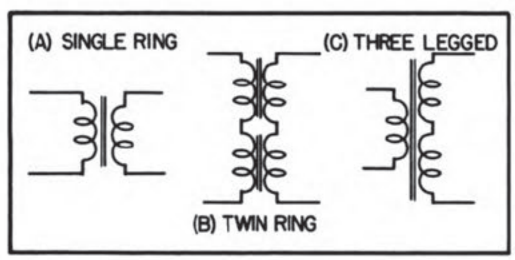

Figure 58-16 - Schematic representation of reactor cores.

Various schematic symbols are used to designate saturable cores and magnetic amplifiers.

The more common ones are illustrated in Figure 58-16-1, examples (a), (b), and (c).

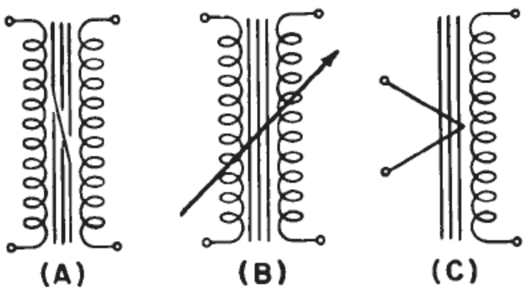

Figure 58-16-1 - Saturable core and magnetic amplifier symbols.

In analyzing the saturable reactor it will be best to discuss the control circuit first. The circuit in Figure 58-17 shows a ferromagnetic core with the control winding, N_C, in series with variable resistor, R, switch, S, and the control voltage source E_{dc}.

When a control voltage, E_{dc}, is present and the switch is closed, current will flow in the control circuit. The amount of current flow in the control circuit can be controlled by R. Therefore, the magnetizing force applied to the core can be controlled by adjusting R.

The B-H curve for the core in Figure 58-17 is shown in Figure 58-18.

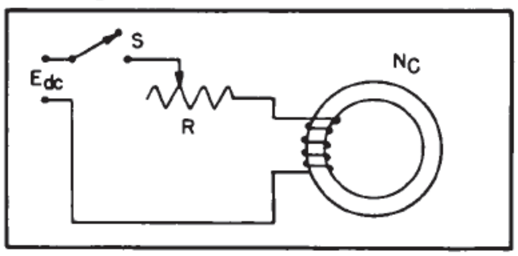

Figure 58-17 - Saturable reactor core and control circuit.

As the control current in Figure 58-18 is increased from zero the flux density increases slowly through area A of the B-H curve and the core permeability is relatively low.

As the control current (magnetizing force) is increased into area B, the flux density increases very rapidly. The core permeability when operated in area B is very high, because a small change in H results in a very large change in B. A further increase in the control current drives the core into saturation, area C. In area C, an increase in H results in a very small change in B; consequently, permeability is very low.

If the load winding circuit is added to the reactor core it completes the saturable reactor circuit as shown in Figure 58-19.

The load circuit consists of the load winding, and a resistor in series with an ac voltage source. The voltage developed across the load resistor is determined by the current in the load circuit. The current flowing in the load circuit is determined by the inductive reactance, X_L, of the load winding and the resistance of

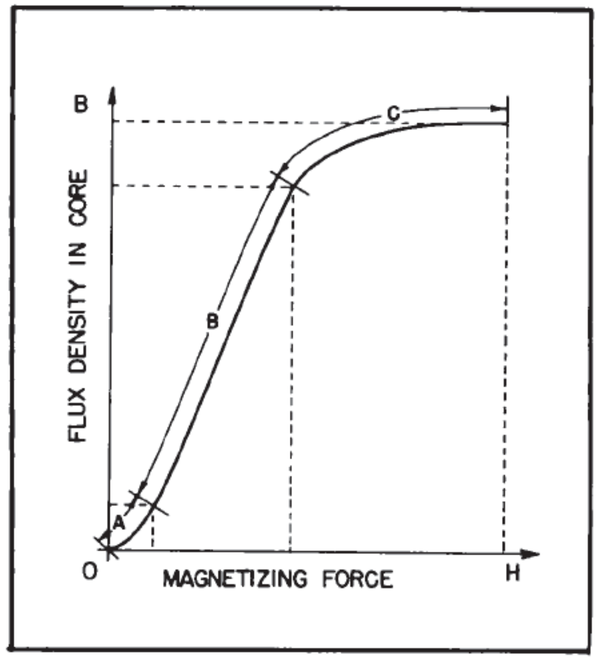

Figure 58-18 - B-H curve for reactor core.

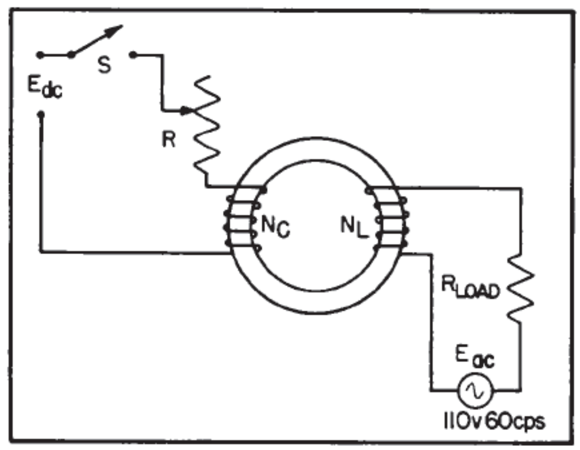

Figure 58-19 - Saturable reactor circuit.

the load resistor. It was pointed out earlier that the inductance of a coil is directly proportional to the permeability, μ, of the core material used and can be found by the formula:

$$L = \frac{1.257\,\mu A N^2}{1m \times 10^8} \qquad (9\text{-}4)$$

The inductive reactance of a coil is directly proportional to the inductance of the coil as illustrated by the formula $X_L = 2\pi f L$.

It was shown also that the permeability of the core can be controlled by varying the control current, which in turn changes the point of operation on the B-H curve. If the control current is set at such a value that the operating point on the B-H curve in Figure 58-18 is in area B, the permeability of the core is very high.

Therefore, the inductance and inductive reactance of the load winding will be very high. The ac current in the load circuit will be very low and the voltage developed across the load resistor will be very small.

If the control current is increased to a point where the core is driven into saturation, the permeability is reduced to a very low value. The inductance and inductive reactance of the load winding will now be very low. Therefore, load circuit current will be high and most of the ac source voltage will be developed across the load resistor. The important fact is that a very small change in control current can cause a large change in core permeability, which in turn results in a large change in load current and voltage across the load resistor. Therefore, a saturable reactor uses a small control voltage variation to vary or regulate large ac load voltages smoothly over a wide range. Saturable reactors find application in controlling the brightness of groups of lights in theaters or controlling electric heaters in industrial furnaces.

The basic reactor circuit of Figure 58-19 is rather inefficient due to alternating current flowing through the load winding. Such currents produce two detrimental effects:

1. Voltage is induced from the load winding to the control winding by transformer action. Since the control winding has low impedance, large currents will flow in the control circuit and cause a large amount of power to be dissipated.
2. During one half-cycle, the load winding current flow will produce a flux which opposes that produced by the control winding. Power from the control windings is required to return the core flux to the normal operating point.

The problem of the opposing flux may be eliminated by placing a rectifier in series with the load winding. The load current becomes unidirectional and if the rectifier is properly connected the flux fields never oppose each other. The addition of the rectifier converts the saturable reactor to a magnetic amplifier. This will be covered in more detail later in the chapter.

Another method of reducing the effects of these problems is the use of a non-polarized, three-legged

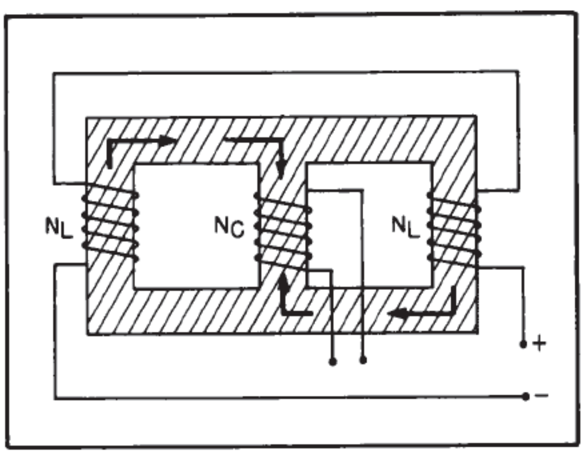

Figure 58-20 - Non-polarized, three-legged core.

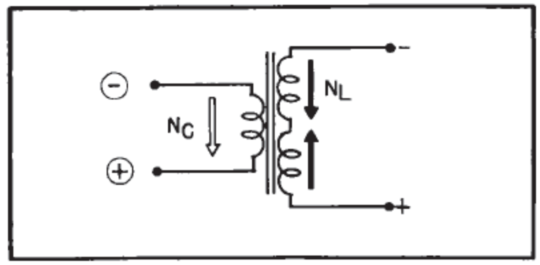

Figure 58-21 - Non-polarized, three-legged core winding.

core as shown in Figure 58-20. The control winding is wound around the center leg. One load winding is would around one outside leg and the other is wound around the opposite leg, in such a manner so that the two flux fields cancel in the center leg.

The schematic representation of the circuit in Figure 58-20 is shown in Figure 58-21. It can be seen that the flux fields produced by the two load windings are in opposition to each other and induce no voltage into the control winding. When the load potential is reversed, the fields produced by each load winding is reversed, the flux fields however, still oppose each other in the center leg. It can also be observed that one flux field aids the control flux and the other opposes it. This permits a control voltage of either polarity to be used. This is the reason for the name "NON-POLARIZED" three-legged core.

In some cases it is necessary to use a three-legged core such as the one shown in Figure 58-22.

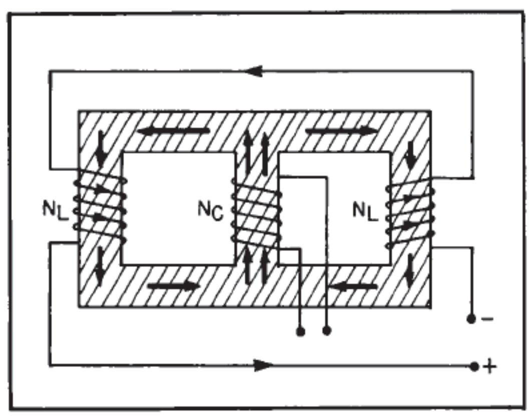

Figure 58-22 - Polarized, three-legged core.

Here the load windings are wound so that the load fluxes add in the center leg. They are series aiding in other words.

The schematic representation of the core in Figure 58-22 is shown in Figure 58-23. The flux fields produced by the two load windings now aid each other in the center leg. The load winding fields may aid the control field and thereby help saturate the core or they may oppose the control field reducing the flux density.

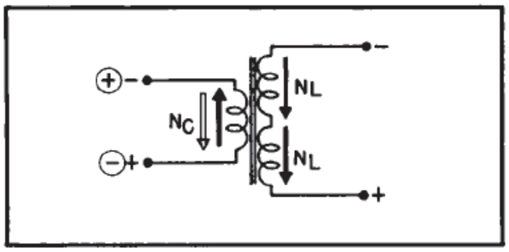

Figure 58-23 - Polarized three-legged core winding.

The polarity of the applied voltages of either the control coil or load coils will determine flux density; the core is therefore said to be POLARIZED.

Q8. What shape core produces the smallest amount of leakage flux?

Q9. Why is it important that leakage flux be kept at a minimum?

58-6. Basic Magnetic Amplifier

The addition of a rectifier, as shown in Figure 58-24 converts the reactor circuit to a magnetic amplifier. In this circuit, the saturable reactor is used in conjunction with a dry-disc rectifier CR_1 to produce a controllable dc voltage across the load resistance R_L.

The reactor contains a three-legged core and since the two load coils produce opposing fields, the reactor is non-polarized. The magnitude of the voltage across R_L is dependent upon the level of the dc control voltage.

First the operation of the circuit with a control winding (N_C) voltage of zero will be considered. When the top of the ac supply is positive

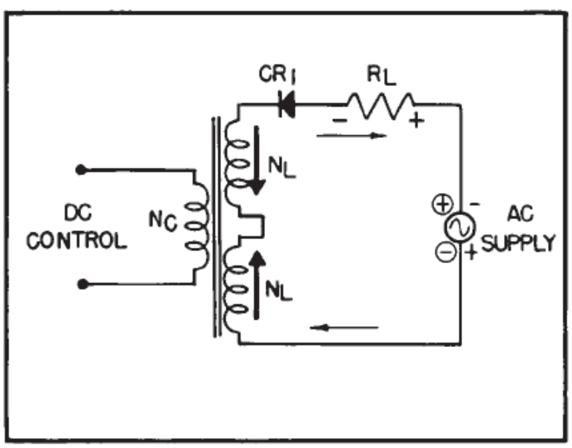

Figure 58-24 - Basic non-polarized magnetic amplifier circuit.

current will flow through the load windings (N_L), CR_1, R_L and back to the source. The absence of a dc potential to saturate the core results in high core permeability; which means that inductance and inductive reactance will also be high. The current flow through the circuit will be very small and the voltage across R_L will be low.

When a dc potential is applied across the control winding, current will flow through the coil and magnetize the core. If the current flow is of sufficient magnitude the core will become saturated and the μ will decrease drastically. The inductive reactance of the load windings will approach zero and current will be high. Hence, the voltage drop across R_L will be large. An increase in control current beyond the point of core saturation would result in an insignificant increase in load current; in practice the increase in current beyond this point is considered to be zero. If the current is decreased to values below saturation the μ of the core will increase, the load current will decrease and the voltage across R_L will decrease.

A dynamic characteristic curve can be plotted, showing the effects of varying control current in any magnetic amplifier. Figure 58-25 plots load current against control current. It should be observed that an increase in control current (up to a point of saturation) results in an increase in load current, in a non-polarized magnetic amplifier, and that the direction of control current is unimportant. An increase in control current in one direction results in the same increase in load current, as does an increase in control current in the opposite direction. The load current never reaches zero, but will only reach a minimum value. The minimum value of load current is called the no signal or quiescent current and it occurs when the control current is zero.

The use of the term no signal current may seem strange, since the control current is dc.

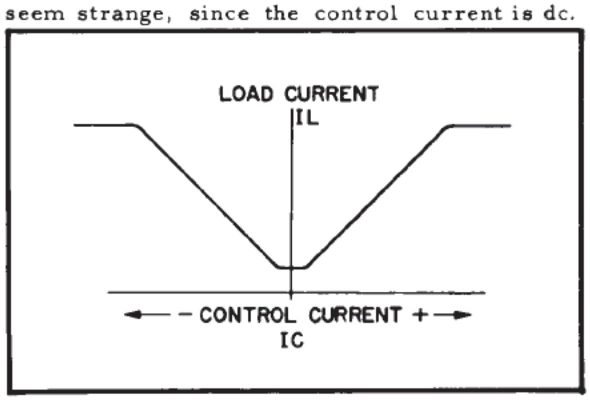

Figure 58-25 - Dynamic characteristic curve of a non-polarized magnetic amplifier.

A8. Toroidal cores produce the smallest amount of leakage flux.

A9. Leakage flux should be kept at a minimum because the loss of flux due to leakage reduces the circuit efficiency.

However, the control signal is analogous to the input signal applied between the control grid and cathode of a vacuum tube. Amplification is achieved in the vacuum tube circuit because a small input potential causes relatively large changes in plate current. In the magnetic amplifier a small change in control current causes large changes in load current.

The load current in a magnetic amplifier is also affected by the size of the load resistor R_L. Figure 58-26 shows an output characteristic curve when load current I_L, is plotted against control current I_C, for two different values of load resistance.

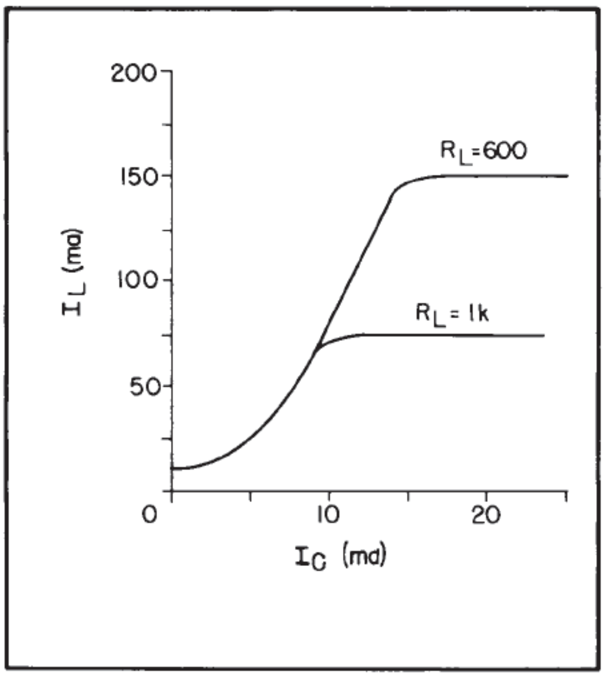

Figure 58-26 - Characteristic curves for different load resistors.

This curve illustrates the fact that the load current is much greater at saturation in the magnetic amplifier which has the smaller load resistor. It should be noted that an increase in control current when operating on the steep portion of the curve will produce a large change in the load current. Consequently it can be seen how amplification is achieved.

Q10. What is the principle of amplification in a magnetic amplifier?

58-7. Magnetic Amplifiers with External Feedback

As with other types of amplifiers, feedback may be used in magnetic amplifiers positively to increase gain or develop regeneration, or negatively to limit gain, improve output waveform, or improve stability. With regard to feedback, magnetic amplifiers can be classed in three groups:

1. Amplifiers without feedback.
2. Amplifiers with external feedback.
3. Amplifiers with internal feedback.

This topic will be concerned with magnetic amplifiers employing external feedback.

A magnetic amplifier with external feedback is one having positive or negative feedback accomplished by means of an external, inductively coupled winding, with load current flowing through it. Usually in these circuits rectified load current flows through a FEEDBACK winding. If the field developed in the feedback winding aids the control winding field, the feedback is regenerative. If the two fields oppose each other the feedback is degenerative. The effect of external feedback on transfer characteristics is as shown in Figure 58-27. A comparison between the two curves reveals that the use of positive feedback results in a non-symmetrical curve, whereas the non-feedback curve is symmetrical. It also shows that unlike the non-feedback circuit, the load current does not reach its minimum when control current is zero; it reaches its minimum when control current is negative.

The amount of feedback will determine the final shape of the characteristic curve, as shown in Figure 58-28. If positive feedback increases, the slope of the curve increases.

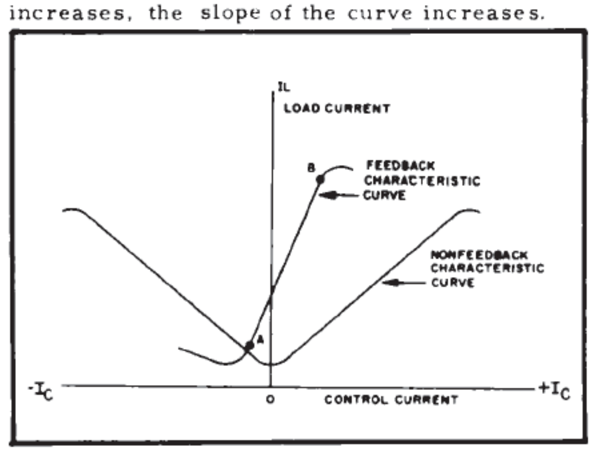

Figure 58-27 - Comparison of positive feedback and non-feedback characteristics.

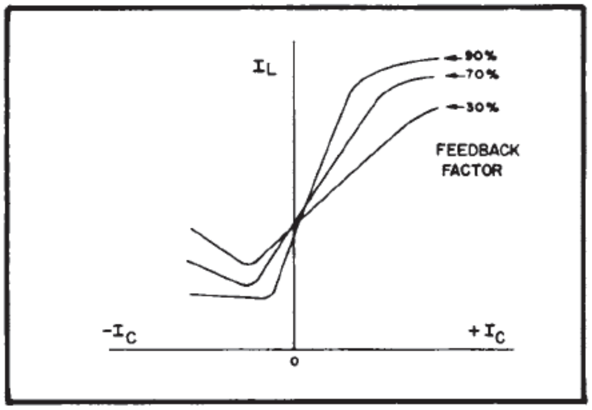

Figure 58-28 - Transfer characteristics with varying amount of positive feedback.

In Figure 58-27 the slope of the curve between points A and B is determined by the percentage of feedback, as shown in Figure 58-28. As feedback is increased, the slope increases so that the load current, for a given change in control current, varies more for a positive feedback amplifier than for the non-feedback amplifier.

It should be understood that both the feedback and non-feedback amplifier require the same total core flux variation to produce a given effect. In a non-feedback amplifier, the flux is produced only by the direct control current. In an external feedback amplifier, the flux is produced jointly by control and feedback currents. In the latter case, if the feedback is regenerative, less control current is needed for a given effect, thus more gain is obtained.

If positive feedback is increased above 100 percent, the amplifier becomes unstable and is likely to "snap" into maximum conduction even when positive control current is very small. To maintain good stability, the feedback factor is usually kept below 85%.

Figure 58-29 shows the graphical and schematic symbols of a reactor using a feedback winding. The terms N_F, N_C and N_L refer to the feedback, control and load windings, respectively. This designation will hold throughout the remainder of this chapter.

Either schematic symbol may be used. The one to the right is frequently preferred due to its simplicity. In such a schematic the control and feedback windings are reduced to single turns and the iron core symbol is eliminated (but understood to be there).

To understand the effects produced by external (positive) feedback refer to the feedback curve of Figure 58-28 as the circuit of Figure 58-30 is discussed.

For purposes of external feedback, a special

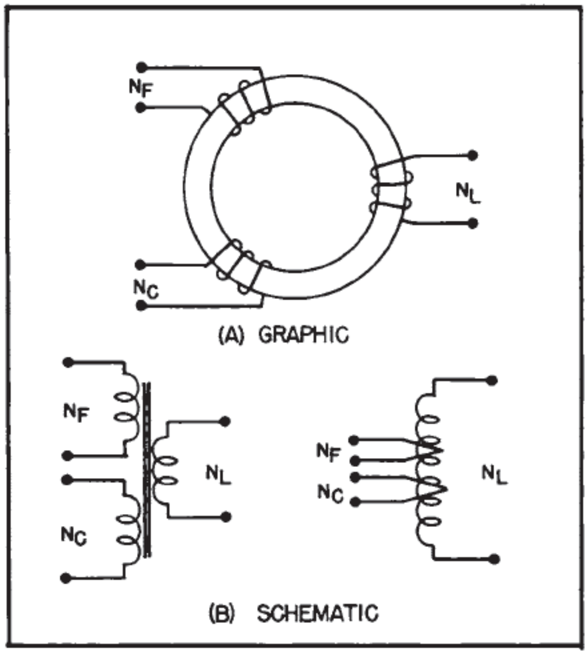

Figure 58-29 - Graphic and schematic symbols of a reactor having a feedback winding.

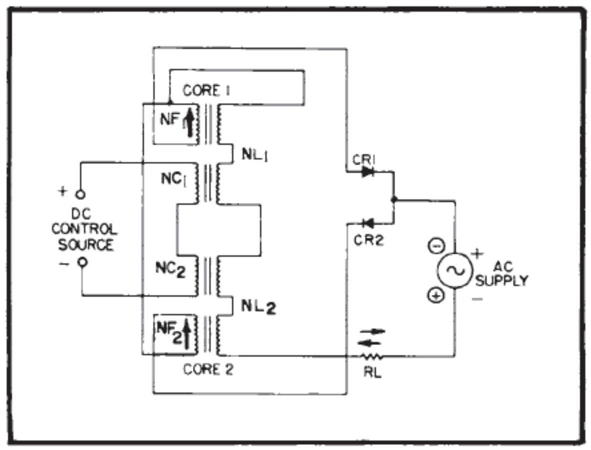

Figure 58-30 - External feedback amplifier with ac load.

winding, a feedback winding, N_F, is added to each reactor. To produce a positive feedback or regenerative effect, the flux produced by this winding must aid that produced by the control winding. For inverse or negative feedback, the fluxes must oppose.

Figure 58-30 shows an elementary positive feedback amplifier capable of operating into an ac load. In following the circuit operation, it will be assumed that the ac supply is on the half-cycle having the circled polarity. Electrons flow from the negative end of the supply through

A10. The principle of amplification in a magnetic amplifier circuit is that a small change in control current (input signal) produces a large change in load current (output signal).

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rectifier CR_1, feedback winding N_{F1}, the series-connected load windings N_{L1} and N_{L2} of both reactors, and load R_L back to the supply. On the next half-cycle, electrons flow through load R_L, both load windings, feedback winding N_{F2}, and rectifier CR_2. Electron flow is always in the same direction through the feedback windings regardless of the supplv half-cycle. Flux produced around the feedback windings therefore always has the same polarity.

This amplifier drives ac load R_L; electron flow through the load changes direction on alternate half-cycles.

If the circuit is operated without control voltage, the quiescent current (the load current that flows when no control current is present) will be higher when positive feedback is used; because the load current also flows through the feedback windings. The current through the N_F coils reduce the permeability of the core and the reactance of the load windings.

For the positive feedback effect, the flux produced by the control windings must be aided by that produced by the feedback windings. The fluxes will aid, producing positive feedback, when the dc control current has the indicated (positive) polarity shown in Figure 58-30.

As a result, total core flux increases and load winding reactance decreases. This causes larger load current to flow and causes the output load voltage to increase. This continues until core saturation is reached.

If control polarity is reversed, negative feedback occurs. The control winding flux opposes that of the feedback winding. If, under this condition, control current is increased, the load winding reactance will increase until the point is reached where control flux and feedback flux are equal. If control current is further increased, control flux overrides feedback flux and load winding reactance slowly decreases causing load current to increase, slowly.

The effective input impedance of a magnetic amplifier is unaffected by extérnal feedback. This is in direct contrast to electronic amplifiers where the circuit input impedance is determined by the feedback. Since feedback current in a magnetic amplifier flows through an isolated winding, the impedance of the input or control circuit is determined only by winding resistance and any series resistance which may be used. It is important to note that such series resistances may be used to increase the response time of the magnetic amplifier, since the time constant (T) for an inductive circuit is the ratio of inductance to resistance, or $T=L/R$; T being in seconds if L is in henrys and R in ohms.

It was stated previously that an increased quiescent current will flow through the load winding of a magnetic amplifier using external feedback. This current can be as much as 50 ma; the actual value being determined by:

1. The amplitude and frequency of the supply voltage.
2. The turns ratio between the feedback and load windings.
3. The physical dimensions of the reactor.
4. The electrical characteristics of the reactor.

Since the feedback is regenerative, the quiescent current will produce sizeable circuit effects and, consequently, must be minimized.

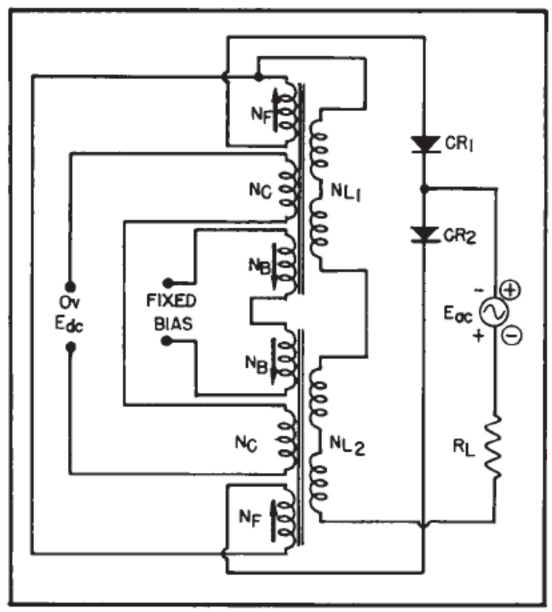

Figure 58-31 - Magnetic amplifier using external feedback and bias.

Quiescent current could be reduced to a minimum if the feedback flux were eliminated at times when no control current is flowing. This may be accomplished by the addition of a bias winding, N_B, to the core of each reactor as shown in Figure 58-31.

The circuit employed in Figure 58-31 is the same one used in Figure 58-30 except that the bias winding has been added to set the operating

point.

Figure 58-32 shows a comparison of characteristic curves for a magnetic amplifier using external feedback without bias and a magnetic amplifier using external feedback with bias.

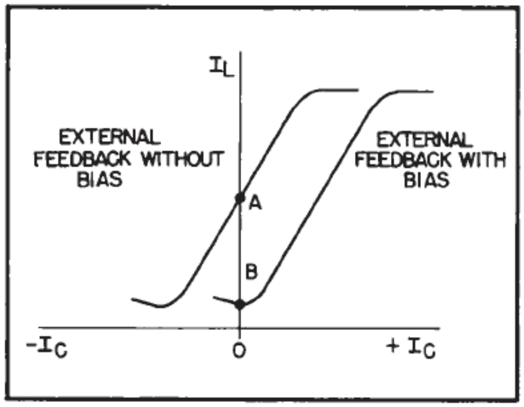

Figure 58-32 - Comparison of external feedback characteristic curves with and without bias.

Operating point A in Figure 58-32 shows that an appreciable amount of quiescent current flows in the magnetic amplifier using feedback windings but not bias. This large amount of quiescent current is due to the flux in the core caused by the current through the feedback windings as pointed out earlier.

Operating point B shows that quiescent current is minimum in the magnetic amplifier using feedback windings and bias. Figure 58-31 shows that the flux developed by the bias windings opposes and cancels the flux produced by the feedback windings when no control field is present. Therefore, there will be minimum flux in the reactor cores at this time and their permeability will be very high. Thus the inductance and inductive reactance of the load windings is maximum and load current, I_L, is minimum in the absence of control current. However, once control current is applied, the feedback current will increase and overcome the bias. Therefore, as shown in Figure 58-32, the bias current has shifted the curve to the right but has not altered the slope of the curve.

By varying the amount of bias, the operating point may be placed at any desired value as shown in Figure 58-33.

Q11. Define a magnetic amplifier having external feedback.

Q12. What happens to the slope of the transfer characteristic curve as the amount of positive feedback increases?

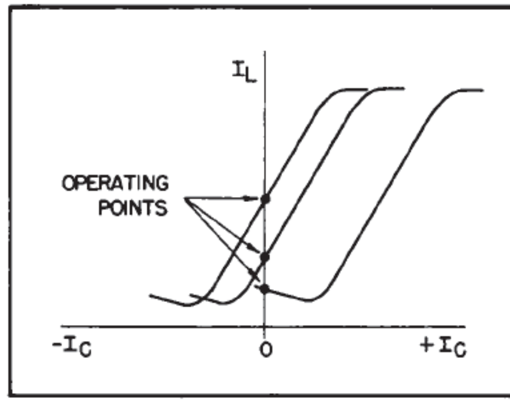

Figure 58-33 - Operating points for several values of bias.

Q13. Why is positive feedback used?

Q14. What advantage has magnetic amplifiers with external feedback over conventional electronic amplifiers with feedback?

Q15. Why was the bias winding added?

Q16. How strong would the field developed by the bias winding have to be and would it aid or oppose the feedback flux if it was desired to have minimum load current in the absence of control current?

58-8. Magnetic Amplifiers with Internal Feedback

Feedback in a magnetic amplifier can be accomplished by having the load winding current produce feedback directly. This is referred to as INTERNAL, INTRINSIC, ELECTRIC or SELF-SATURATED FEEDBACK. In circuits using this type of feedback, a rectifier is connected in series with the load so that dc flows through the load windings. If a three-legged core is used, the load windings are wound so that their fields are series aiding in the center leg of the core. Due to its manner of operation, an internal feedback magnetic amplifier is one which uses a self-saturation (auto-excited) circuit.

If the characteristics of internal and external feedback amplifiers are compared, little difference between the two is seen. The advantage of self-saturation, however, is the elimination of feedback windings resulting in a simpler re-

A11. One in which feedback (positive or negative) is accomplished by an external inductively coupled winding having load current flowing through it.

A12. The slope increases.

A13. To provide a greater gain.

A14. The input impedance of the magnetic amplifier is unaffected by external feedback.

A15. The bias winding sets the operating point of the magnetic amplifier.

A16. The bias field should be set equal to the feedback field and they should be opposing.

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actor. Through the elimination of feedback windings, three advantages are gained:

1. It simplifies reactor construction.
2. It eliminates the resistance of the external feedback winding through which the load current must flow.
3. It allows the load winding to be wound over a larger portion of the reactor frame, thereby permitting a greater power output for a given frame size.

On the other hand, use of external feedback allows the amplifier gain to be easily adjusted.

In an earlier discussion, it was mentioned that inductive reactors are capable of amplification because of core saturation. When the core becomes saturated the impedance is low, when not saturated the impedance is high. In the basic magnetic amplifier a rectifier is placed in series with the load and the ac supply voltage so that current will flow in only one direction through the load windings. As a result, when a dc control voltage is applied, the core flux level will never decrease below a specified minimum as determined by the amount of control current. A basic self-saturating magnetic amplifier circuit is shown in Figure 58-34. The determining factor in this self-saturating magnetic amplifier is the rectifier.

The circuit will first be analyzed without the presence of a control voltage. During the ac input alternation indicated by the circle polarity there will be no current flow in the load windings, since CR_1 opposes the flow current at this time. During the next alternation as indicated, the resistance of CR_1 is low and allows the flow of current through R_L and N_L.

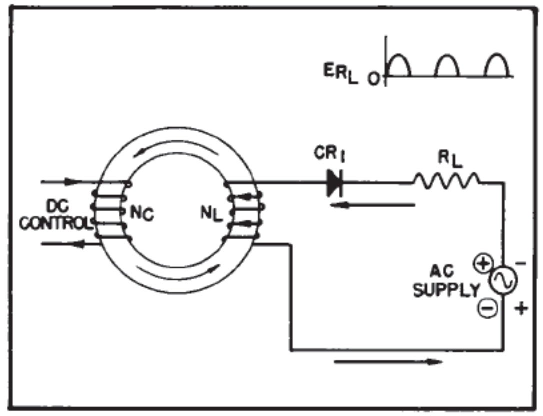

Figure 58-34 - Basic self-saturating magnetic amplifier.

The pulsating current flow through the load winding increases the flux density causing the reactance of the load winding to decrease and more current to flow through R_L. Thus, we have the principle of self-saturation.

If a control voltage of the polarity indicated is applied to the control winding, the current will produce a flux that will aid the load current flux and therefore, increase the core saturation and lower the impedance of the load winding. This lower reactance will cause a larger load current and the voltage across R_L increases. However, the increased load current causes the core flux to increase further as the load flux aids the control flux. Load winding reactance will now decrease still more and load current will increase to a higher value. The load flux has aided the control flux and is regenerative. A magnetic amplifier using the self-saturation principle is said to have internal feedback.

If the control voltage is reversed, current in the control winding will be such that the load flux will oppose the control flux. This will cause the reactance of the load winding to increase. As a result of this, the load current will decrease and consequently a lower output voltage will be felt across the load. The internal feedback is now degenerative. Thus, it can be seen that this is a polarized magnetic amplifier in that it can distinguish between the polarities of the control input voltage.

To produce a full sine wave output a two reactor magnetic amplifier circuit as illustrated in Figure 58-35 may be used. In this circuit a dc control input voltage is also used.

First assuming that no dc control voltage is present and the ac supply being that of the uncircled polarities, current will flow from the ac supply through R_L, CR_2, N_{L2} and back to the source. On the half cycle in circled polari-

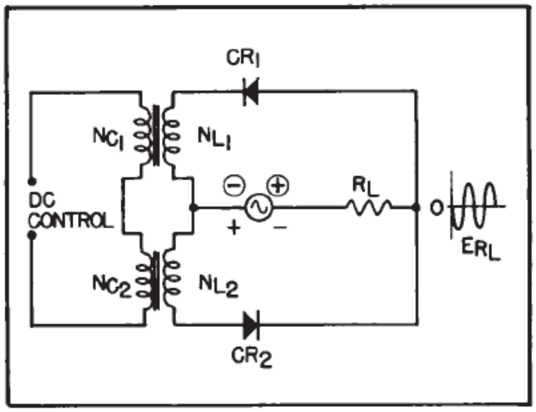

Figure 58-35 - Magnetic amplifier, two reactor doubler circuit.

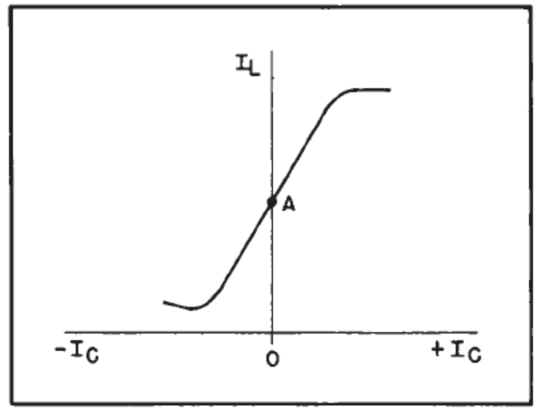

Figure 58-36 - Transfer curve for circuit using internal feedback.

ties, current will flow through N_{L1}, CR_1, R_L and back to the source. In Figure 58-35 the load windings N_{L1} and N_{L2} are wound so that their fields are series aiding in the center leg of their respective cores.

Note that the voltage drop across R_L will reverse on each half-cycle producing an ac across the load.

The polarity of the input dc will determine the amplitude of the ac across R_L. As in the previous example the polarity of the input dc will determine the magnitude of the flux produced in the reactor core. With a dc of the polarity shown, the flux produced in the control winding will aid the flux produced in the load winding. When this occurs, the impedance of the load winding will decrease and the load current will increase, thus producing a greater voltage drop across R_L. The increased load current causes a greater flux to be developed in the core. The load winding reactance decreases further and load current will increase. Thus, it can be seen that since the load flux aids the control flux, the internal feedback is regenerative. An increase in the dc input will cause the load voltage to increase until such time as the core is saturated. When this happens load current can no longer increase.

When the control voltage is reversed, the flux produced in the core will oppose that produced by the load current. This will cause the impedance of the load windings to be of a high value, resulting in a low output voltage. If the control voltage is increased the output will decrease to a minimum at such time as the load flux and the control flux are equal and cancel completely. Any further increase in control voltage will cause the flux in the core to increase thus decreasing the load winding impedance. The load current will increase very slightly, however as the increased load flux opposes the control flux, therefore reducing the overall flux in the core. The internal feedback is now degenerative. The transfer curve for the circuit in Figure 58-35 is shown in Figure 58-36.

The large amount of quiescent current (point A) is due to the high level of load flux in the core. The positive control current flux was aided by the load flux and the regeneration provided more gain. Negative control current flux was opposed by the load flux and degeneration occurred resulting in reduced gain. This circuit is therefore a polarized magnetic amplifier in that it can distinguish between the different polarities of control voltage. A bias winding may be added to set the operating point if desired.

Q17. Define a magnetic amplifier having internal feedback.

Q18. What are the advantages of internal feedback over external feedback?

Q19. In the two-core internal-feedback amplifier, what determines the amplitude of the ac voltage developed across the load?

58-9. Magnetic Amplifier Servo System

In the positioning system shown in Figure 58-37, a comparison is constantly made between the position of the input shaft (also called a controlling shaft) and the position of the controlled shaft. Any difference between the two shaft positions causes the synchro follow-up

A17. One which uses a self-saturating circuit in that load winding current produces feedback directly.

A18. (1) Simplifies reactor construction
(2) Reduces the resistance through which load current flows.
(3) Allows a greater portion of the reactor frame to be used by the load winding, thereby increasing the power output capability for a given sized core frame.

A19. The polarity and magnitude of the control current.

(control transformer) to extract an error signal. The phase of the error signal is determined by the direction of displacement between the two shaft positions. The error signal is applied to a phase-sensitive detector that produces a dc output, the polarity of which depends on the error signal phase while the magnitude corresponds to the error signal amplitude. This dc signal, in turn, drives a push-pull magnetic amplifier which produces a phase-reversible signal to drive the servo in the proper direction. The servo motor causes the output load shaft to turn, thereby positioning the load. Mechanically connected to the output load shaft is a gear train reduction system which provides mechanical feedback to turn the controlled shaft. As this shaft turns, the displacement between controlling and controlled shafts decreases, thereby reducing the error signal by a corresponding amount. When the servo motor has driven the output load shaft to the position indicated by the input shaft, the controlled and controlling shafts will have no displacement with respect to each other, the error signal will be reduced to zero, and the servo motor will stop driving.

Since the operation of the control transformer, control transmitter, and servo motor were explained in Chapter 57, their operation will not be considered at this time. The gear train reduction provides a means of compensating for mechancial differences between the output load shaft and the controlled shaft.

The two circuits of Figure 58-37, which will receive detailed consideration in this topic, will be the phase-sensitive detector and the push-pull magnetic amplifier.

The phase sensitive detector (or demodulator) is a circuit designed to provide a dc output, such that the output polarity is determined by the input phase while the output magnitude is determined by the input amplitude. To detect a reversal in phase of an ac signal, it is necessary to compare it to a fixed ac reference having the same frequency. Figure 58-38 shows a simple phase-sensitive detector using a two-core, half-wave magnetic amplifier.

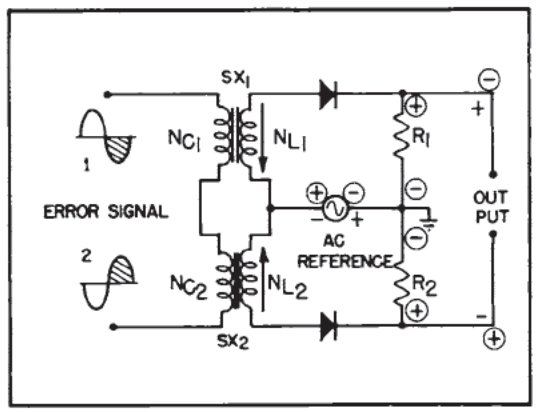

Figure 58-38 - Half-wave amplifier phase-sensitive detector.

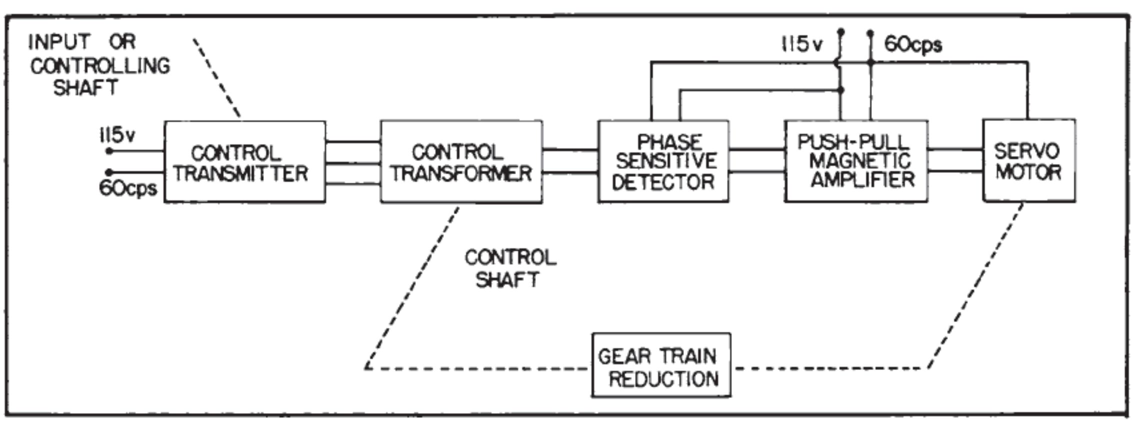

Figure 58-37 - Positioning servo system.

To understand the operation of the phase-sensitive detector shown in Figure 58-38, consider the circuit with no error signal applied and with the ac reference at the alternation shown by the circled polarities. During this half-cycle, current flows from ground through R_1, CR_1, and N_{L1}, to the positive ac reference. The heavy arrow shows the direction of the flux produced in SX_1 by the current through N_{L1}. At the same time current flows through R_2, CR_2, and N_{L2} to the positive ac reference. The heavy arrow shows the direction of flux produced in the SX_2. Note that the direction of flux produced in the two cores is opposing. If the two circuits are identical, the current through R_1 and R_2 will produce equal voltages of the polarities shown. It can be seen that no difference in potential exists between the output leads; consequently, there is no output.

Again consider no input error signal applied, with the ac reference of the alternate half-cycle (shown by the uncircled polarities). Due to the action of CR_1 and CR_2, no current can flow through R_1 and R_2 during this half-cycle, consequently, there is still zero output. Since no output can exist during this half-cycle (due to the rectifier) whether or not an error exists, one-half of the error input will serve no purpose. Considering that the first alternation of either error signal occurs during the circled polarity of the reference signal, the second alternation will have no effect and is, therefore, blacked in.

When error signal #1 is applied, current will flow from ground through N_{C2} and N_{C1}. This causes a flux in SX_2 which aids the flux caused by load winding current. The core saturates very quickly and current through R_2 increases. The current through N_{C1}, however, produces a flux opposite to that produced by N_{L1}. As a result, the reactance of N_{L1} increases and current through R_1 decreases. The large positive voltage developed across R_2 compared with the small positive voltage across R_1 creates a difference of potential across the output leads as shown by the circled polarities. It can be seen that the larger the error signal amplitude, the greater the dc output.

When error signal #2 is applied, current flows down to ground through N_{C1} and N_{C2}. Under this condition, SX_1 becomes saturated while SX_2 becomes less saturated. As a result, current through R_1 becomes greater than that through R_2 producing a dc output shown by the uncircled polarities.

One important disadvantage of the circuit shown in Figure 58-38 is that output pulses at the supply fundamental frequency (usually 60 cps) appear across the load, since the output current is half-wave rectified. This can generate serious problems in magnetic amplifier servo applications.

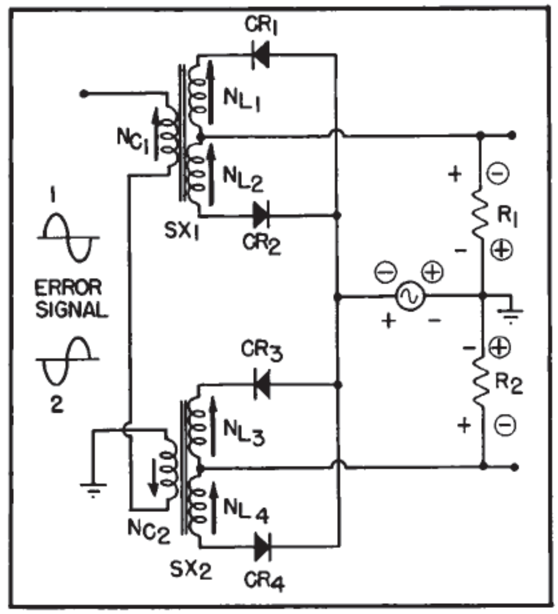

Figure 58-39 - Full-wave phase-sensitive detector.

Through the use of a full-wave rectifier circuit connected as shown in Figure 58-39, the output will not be at the supply frequency.

To understand the operation of the full-wave phase-sensitive detector it is assumed that only the ac reference is applied. During the half-cycle shown by circled polarities, current flows through two paths. One path is through CR_2, N_{L2}, and R_1, the other path is through CR_4, N_{L4}, and R_2. The potentials developed across R_1 and R_2 are of equal negative values (shown by circled polarities across the resistors). Consequently, no difference in potential exists across the output terminals.

During the alternate half-cycle of ac reference (uncircled polarities), current flows through two paths, one made up of R_1, N_{L1} and CR_1; the other made up of R_2, N_{L3} and CR_3. The potentials developed across R_1 and R_2 are of equal positive values (uncircled polarities across resistors). Again, no difference in potential exists across the output terminals. It can be seen, therefore, that with no error signal there is no output.

It it is considered that the first half-cycle of the error signal coincides with the circled polarity half-cycle of the reference and assumed that the phase indicated by error signal #1 is applied, SX_1 will saturate while SX_2 becomes less saturated. As a result, the current of

reference during this half cycle will increase through R_1 but decrease through R_2. This will result in a net difference of potential across the output leads such that the upper lead is negative with respect to the lower.

During the second half cycle of error signal, current flows through N_{C1} and N_{C2} to ground. This causes SX_1 to move away from saturation while SX_2 becomes saturated. This time, current from the ac reference (uncircled polarity) is greater through R_2 than R_1. However, since the current through R_1 and R_2 has reversed, the resultant difference in potential between the output terminals is the same as during the first half-cycle; that is, the upper lead is still negative with respect to the lower. It can be seen, therefore, that with an error signal of phase #1 a dc of a certain polarity is generated between the output terminals. Since the amplitude of the error signal determines the degree of the unbalanced magnetization between the cores, the magnitude of output dc is proportional to error signal amplitude.

If the phase indicated by error signal #2 is applied during the first half-cycle current flows through N_{C1} and N_{C2} to ground. This causes SX_2 to saturate while SX_1 becomes less saturated. Since this corresponds to the half-cycle of ac reference shown by the circled polarities, current through N_{L4} will be greater than through N_{L2}. This will cause a difference of potential between the output terminals such that the upper lead is positive with respect to the lower. It should be noticed that this output is of the opposite polarity than the output for error signal #1.

During the second half-cycle of error signal #2, SX_1 becomes less saturated. This causes the current through N_{L1} to be greater than that through N_{L3}. As a result, the upper output lead is still positive with respect to the lower; so that, the same output polarity is produced for both half-cycles of error signal #2. Again, the magnitude of the dc output is proportional to the error signal amplitude.

Since the output pulses are full-wave rectified, the fundamental frequency is twice that of the half-wave phase-sensitive detector considered previously. This full-wave detector is more efficient, because both alternations of the reference signal are used.

The function of the push-pull magnetic amplifier used as a phase-sensitive detector is to provide amplification, and an output that indicates the direction and amount of the error.

Most servo systems employ a two-phase induction motor to position the load. The direction of rotation in such a motor is dependent upon the phase of the ac signal, while the speed is proportional to the signal amplitude. The required output to drive such a servo motor is obtained from a magnetic amplifier such as is shown in Figure 58-40. Note the similarity of this circuit to the phase-sensitive detector shown in Figure 58-39.

In the circuit of Figure 58-40, the bias windings minimize quiescent load winding current. With no control signal applied, the reactances of N_{L1} and N_{L2} are high and equal. The small current which flows through the field wind-

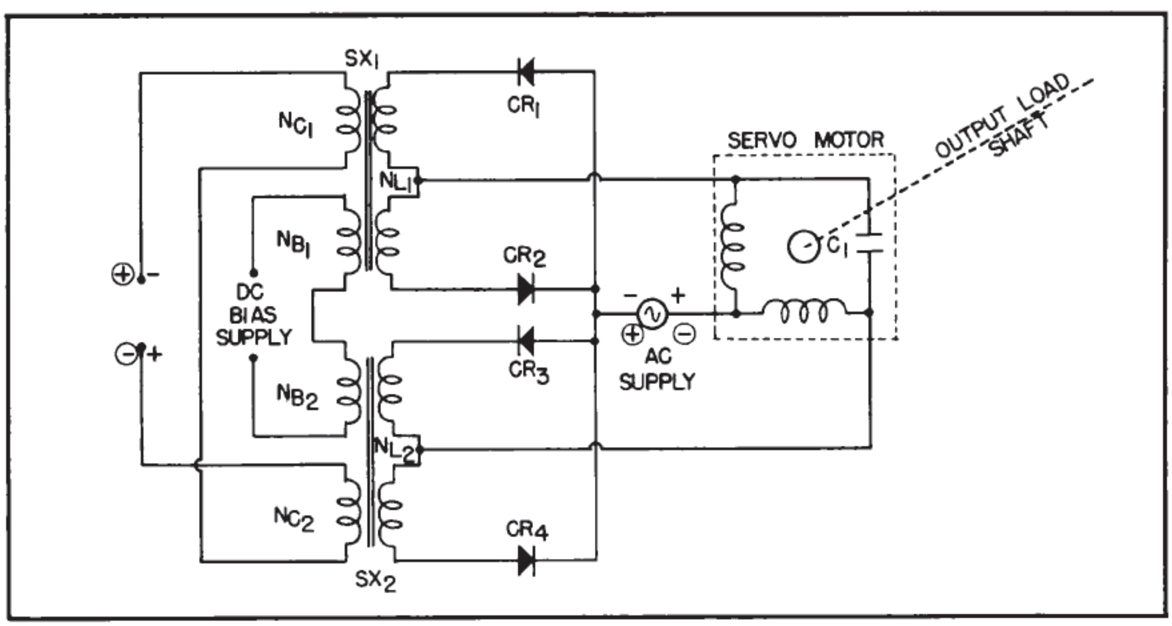

Figure 58-40 - Push-pull two-phase servo motor amplifier.

ings of the servo motor during this condition produce opposing effects. Consequently, the rotor of the servo motor remains stationary.

During quiescence (no control signal), the small load winding currents flow in parallel paths during each half-cycle of the ac supply, as is shown in parts A and B of Figure 58-41.

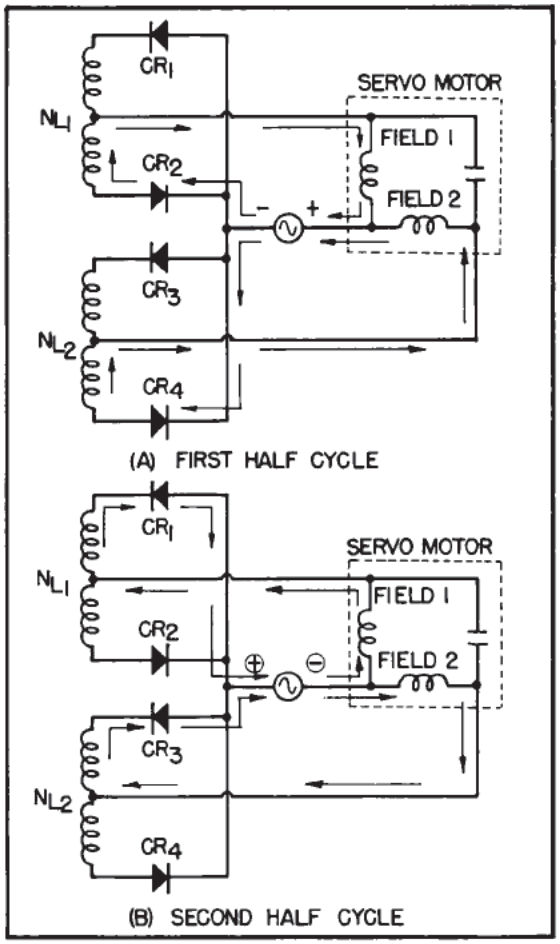

Figure 58-41 - Quiescent current flow in the push-pull servo amplifier.

As can be seen in Figure 58-41, quiescent current flows through both servo motor field windings. Since the two field winding currents are equal, opposing torques of equal amounts are produced which cancel each other out, leaving the motor rotor unaffected. It can be said, then, that with no control signal, no output exists.

The control windings of the two reactors, Figure 58-40, connected series opposing, so that a given polarity of control current will increase the degree of core flux of one reactor while the opposite polarity of control current will increase the degree of core flux in the other reactor.

If the circled polarity of control voltage (Figure 58-40) is now applied, SX_1 approaches saturation and the reactance of N_{L1} decreases. Since this reactor controls the current through field #1 of the servo motor, the decrease in N_{L1} reactance will allow more current through field #1. The reactance of N_{L2} remains high so that very little current flows through field #2. A resultant torque is generated within the motor causing the rotor to turn the output load shaft in a certain direction. The larger the output signal from the phase-sensitive detector, the greater the change in N_{L1} reactance and, therefore, the greater the current through field #1; the end result being that rotor speed varies, roughly, in proportion to the magnitude of the original error.

If the control winding signal is of the uncircled polarity, SX_2 will approach saturation. The reactance of N_{L2} will decrease, thereby allowing more current to flow through field #2 of the servo motor. Under this condition N_{L1} has a relatively high reactance and the current through field #1 is low. A resultant torque is produced which causes the rotor to turn in a direction opposite to that considered above. Again, the speed is roughly proportional to the magnitude of the original error.

A circuit which provides a reversible phase output employing the principle of a balanced impedance bridge can be used to drive a servo motor. Such a circuit is shown in Figure 58-42. R_1 and R_2 serve as current shunts to limit feedback currents.

Effectively, the circuit of Figure 58-42 is a balanced impedance bridge, as long as no control winding current flows. To understand the manner in which the bridge is formed, consider the entire circuit from pin 5 of T_1 to output lead #1 as forming an impedance Z_2. In like manner consider the entire circuit from pin 3 of T_1 to output lead 1 as forming an impedance Z_1. If the impedances are placed in block diagram form, it will be seen that the legs of the impedance bridge are formed by each half of T_1 secondary along with Z_1 and Z_2. This is shown in the simplified diagram of Figure 58-43.

It can be seen from Figure 58-43 that, since T_1 secondary is center-tapped, the bridge is balanced as long as Z_1 and Z_2 are of equal impedances. With the bridge balanced, no difference in potential exists between output lead 1 and 2. This balanced condition exists as long as no control current flows through the reactor control windings.

If control current does flow, it can be either positive or negative. For one direction of control current, the core of reactor 1 becomes

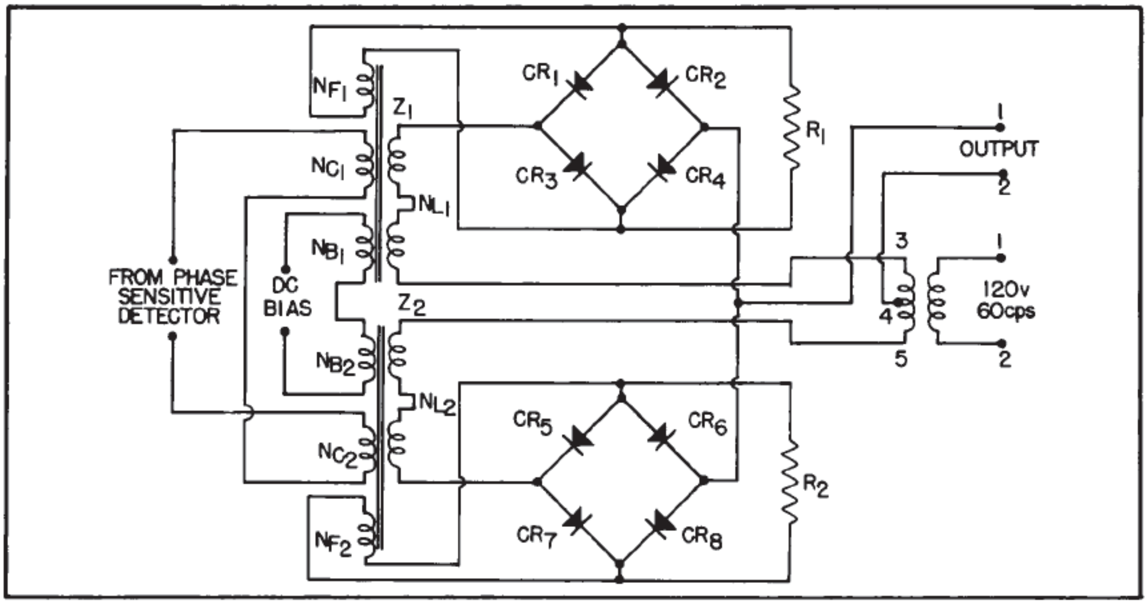

Figure 58-42 - Balanced magnetic amplifier for a two-phase servo motor.

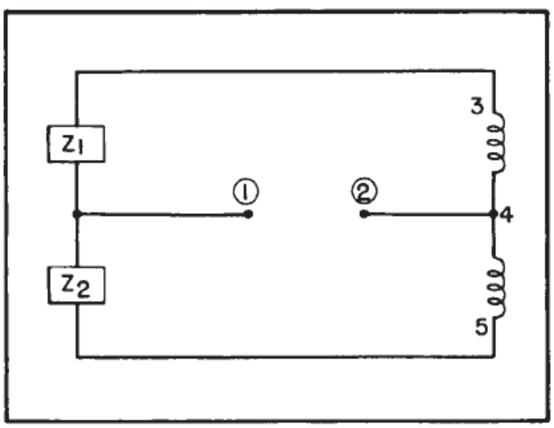

Figure 58-43 - Simplified diagram of balanced magnetic amplifier.

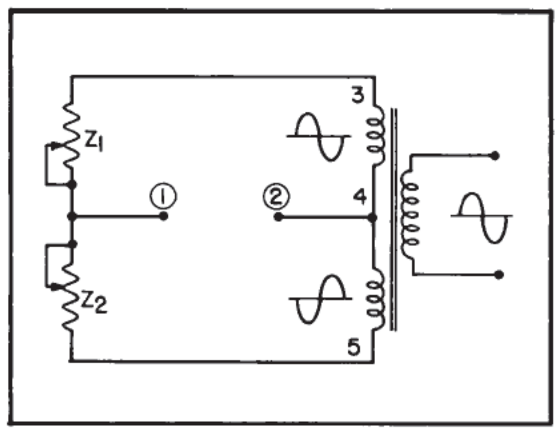

Figure 58-44 - Simplified bridge circuit.

saturated and Z_1 decreases in impedance. For the opposite direction of control current, the core of reactor 2 becomes saturated and Z_2 decreases in impedance. Either of these conditions will unbalance the bridge and produce an output. In one case the output ac will be of one phase while in the other case the output ac will be of opposite phase. A better understanding of this phase reversal can be achieved by referring to the simplified bridge circuit of Figure 58-44.

The two variable resistors in Figure 58-44 represent Z_1 and Z_2 of the original bridge circuit. If the wiper arms of Z_1 and Z_2 are at their center, initially, the two resistances are equal; consequently, each resistor drops half of the TOTAL secondary voltage (the voltage between point 3 and 5, which is twice the voltage between either end and center tap).

To simplify matters, Z_1 and Z_2 can be represented by a variable resistor as shown in Figure 58-45; the portion of the resistor from the wiper arm to the top being Z_1 while the portion from the wiper arm to the bottom being

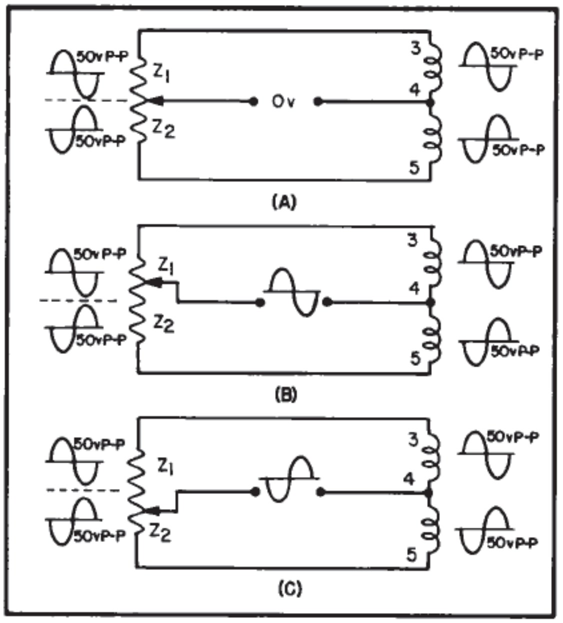

Figure 58-45 - Balanced and unbalanced simplified impedance bridge.

Z_2. If the wiper arm is centered, each half of the resistor drops half of the total secondary (50V peak-to-peak, for the illustrated example). Using the transformer secondary center-tap (pin 4) as a reference point, the wiper arm potential under balanced conditions is zero (part A of Figure 58-45).

Moving the resistor wiper arm above center (part B of Figure 58-45) causes Z_1 to drop less than half the total secondary voltage while Z_2 drops more than half the total secondary voltage. The resultant potential at the wiper arm has a phase corresponding to that induced in the upper half of the transformer secondary and an amplitude determined by the amount that Z_1 and Z_2 changed values (how far up from center the wiper arm moved).

If the impedance of Z_1 increases and Z_2 decreases from their balanced values, this would place the wiper arm below the center of the resistor (as shown in part C of Figure 58-45). Under this condition, Z_1 would drop more than half of total secondary voltage and Z_2 would drop less than half of total secondary voltage. The resultant potential at the wiper arm has a phase corresponding to that induced in the lower half of the transformer secondary. The amplitude of this potential is determined by the amount Z_1 and Z_2 changed values (how far down from center the wiper arm moved).

In the power amplifier of Figure 58-46, the load windings of reactors Z_1 and Z_2 are connected in series through bridge rectifier circuits. With no control winding signal, the reactances of N_{L1} and N_{L2} are equal. Current flow through the load winding circuits for each half-cycle of transformer secondary voltage is shown in the simplified circuit of Figure 58-46. Since the total impedance of Z_1 and Z_2 output circuits are equal with no control winding current, exactly half of total secondary voltage is dropped across

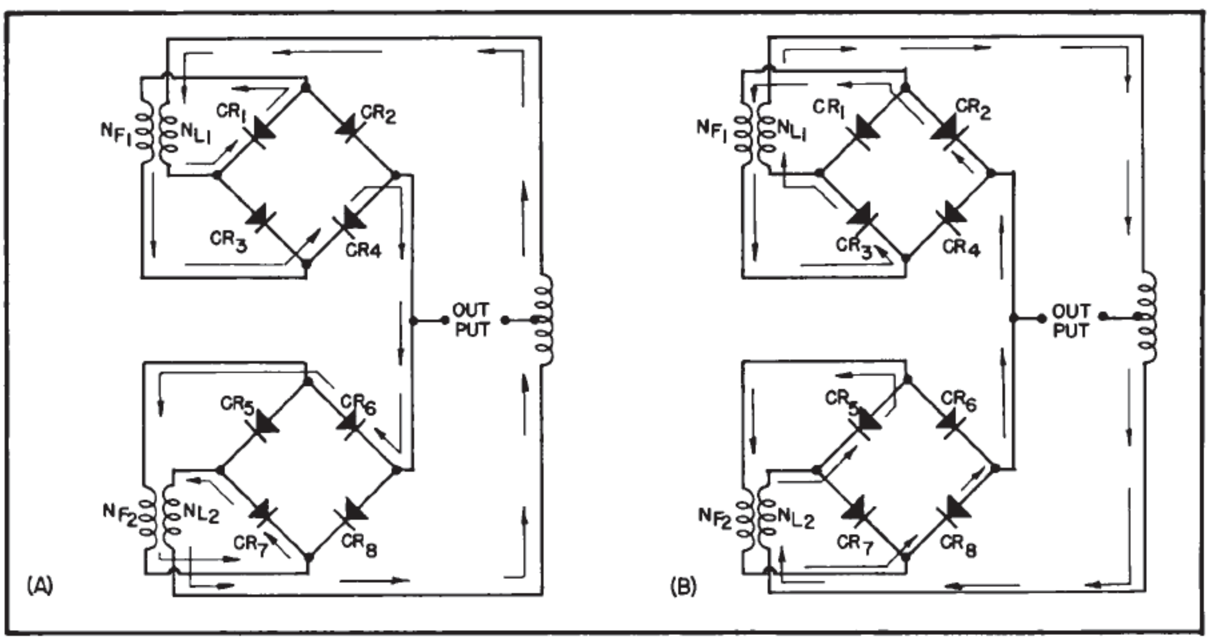

Figure 58-46 - Current flow in the load winding circuits of a balanced bridge amplifier.

each impedance network and no output signal is produced.

In analyzing Figure 58-46, it can be seen that dc flows through the feedback windings. This provides regenerative feedback to increase gain. By connecting the load windings of the two reactors in series opposing, alternating current is allowed to flow through them without upsetting the impedance balance. A better understanding of this can be accomplished by referring to Figure 58-47. For simplicity, the rectifier circuits are eliminated and the load windings are connected directly.

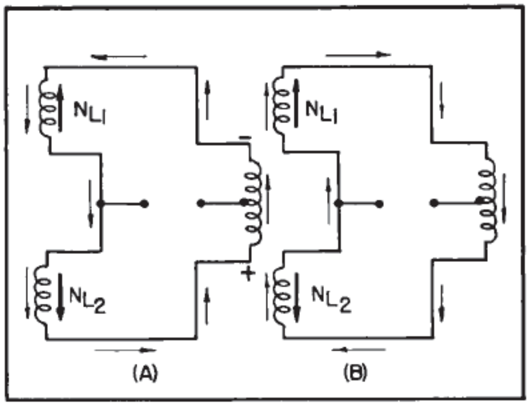

Figure 58-47 - Effects on core saturation with ac load winding current.

For the half-cycle shown in part A, current through N_{L1} increases the flux of core #1, as shown by the heavy arrow. This same current flows through N_{L2}, which is connected series opposing. Consequently, the current through N_{L2} will cause a core flux opposite that of core #1. However, this is the direction in which the core is magnetized. As a result, the flux of core #2 will increase by the same amount as that in core #1 and the RELATIVE IMPEDANCE OF THE TWO WINDINGS WILL REMAIN THE SAME. During this half-cycle, then, the bridge impedance remains balanced. For the half-cycle shown in part B load winding current will oppose core magnetization in BOTH cores by the same amount. This will cause a corresponding decrease in the flux of both cores and an increase in the reactance of both windings. Since the reactance increase is the same for both windings; again, the relative impedance of the load windings remains unchanged. As a result, ac flowing through the load windings will not affect the relative impedance of Z_1 and Z_2.

The two control windings are connected series aiding so that for one polarity of input signal, the resultant flux will increase core magnetization in one reactor while decreasing it in the other. With the application of the opposite polarity input signal the core conditions will reverse. This is shown in the partial circuits of Figure 58-48. The light arrows indicate the flux produced by the control windings while the heavy arrows indicate the resultant flux in each core.

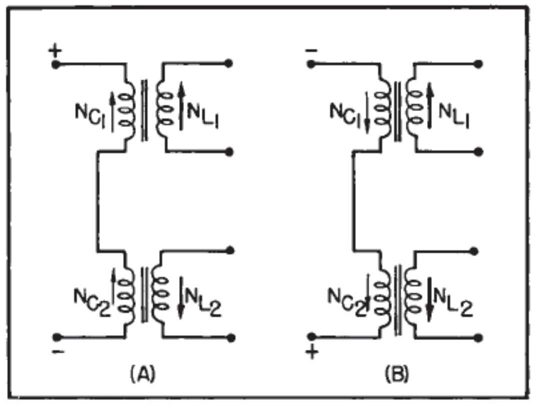

Figure 58-48 - Control winding effects on core flux.

Consider that the amplifier input signal is of the polarity shown in part A of Figure 58-48. This causes the flux of core #1 to increase and the flux of core #2 to decrease. As a result, the reactance of N_{L1} decreases while the reactance of N_{L2} increases. This causes an unbalanced impedance condition which was previously shown by Figure 58-45 (circuit B). Due to this unbalance, an output ac signal is produced. The phase of this voltage is the same as the phase of the voltage induced in the upper half of T_1 primary (Figure 58-48). This output signal will cause the servo motor to drive in a given direction.

With an input signal of the polarity shown in part B of Figure 58-48, the flux of core #1 decreases while that of core #2 increases. This causes the reactance of N_{L1} to increase while the reactance of N_{L2} decreases. As a result, the bridge network becomes unbalanced. Due to this unbalance an output ac is produced which has the phase of voltage induced in the lower half of T_1. This output will cause the servo motor to drive in a direction opposite to that which resulted when the input signal was of the original polarity.

Since the degree of unbalance in the bridge circuit is determined by the magnitude of the input signal, the amplitude of the output signal will vary in proportion to input magnitude.

A variety of other magnetic amplifiers have been designed for operation in servo systems. These usually include multiple-winding, multi-

ple-core reactors. In some instances stages are cascaded to develop the required power output. Some servo magnetic amplifiers include a special STABILIZING winding to provide stabilization of the servo system, thereby eliminating the need for control networks designed specifically to serve this function.

Q20. What is a phase sensitive detector?

Q21. What advantages do full-wave phase-sensitive detectors have over half-wave type?

Q22. What is the function of a servo motor driver amplifier?

Q23. What prevents the servo motor (Figure 58-46) rotor from turning with no control winding input?

Q24. In Figure 58-42, if R_1 and R_2 were made adjustable, what function would they serve?

Q25. In Figure 58-42, what would be the relative polarities of output leads 1 and 2 if the reactance of N_{L1} were greater than N_{L2} and the instantaneous polarity of T_1 secondary was pin 3 positive and pin 5 negative?

A20. A circuit that provides a dc output of polarity and magnitude which corresponds, respectively, to the phase and amplitude of the ac input signal.

A21. (a) The full-wave circuit is more efficient.
(b) The full-wave output is twice the reference fundamental frequency.

A22. (2) To provide power gain.
(b) To provide an output that indicates the direction and amount of error.

A23. Equal currents flow through both field windings of the servo motor, creating equal and opposite torques which completely cancel out.

A24. They would provide a means of varying the amplifier gain by varying the amount of feedback current.

A25. The relative polarities of the output leads would be the same as the relative polarities of pin 5 to pin 4 of T_1 secondary; that is, output lead 1 would be negative with respect to output lead 2.

EXERCISE 58

1. Define flux density, magnetizing force, reluctance and permeability.
2. What is a magnetization curve?
3. Would it be correct to say that a magnetic amplifier acts as a variable inductance? Explain.
4. What is a hysteresis curve?
5. What is coercive force?
6. Explain the core losses of saturable reactor devices.
7. What core shape is generally used in magnetic amplifiers? Why?
8. What advantage has the three-legged core? Disadvantage?
9. What is meant by UI and EI core construction?
10. Describe the purpose of the control and load windings.
11. What is the requirement to produce a counter EMF?
12. Explain how core permeability is varied in a saturable reactor.
13. What are the disadvantages in using a single core saturable reactor?
14. What is meant by the terms "gating", "reset", and "firing point"?
15. What is the function of a bias winding?
16. Describe the characteristics of a bias-polarized amplifier. A duo-directional amplifier.
17. How are external and internal feedbacks accomplished?
18. What controls the slope of a magnetic amplifier transfer characteristic curve?
19. What controls the lateral position of a transfer characteristic curve?
20. Describe the effects of positive feedback. Negative feedback.
21. How can the response time of a particular magnetic amplifier be increased?
22. What factors determine the value of quiescent current in a magnetic amplifier?
23. What is the advantage in using external feedback over internal feedback?
24. Does biasing of a magnetic amplifier necessarily require a biasing winding? Explain.
25. For what application are saturable core devices most frequently used?
26. List at least 5 advantages and 3 disadvantages of magnetic amplifiers.
27. Explain the general operation of a positioning servo system.
28. Why are half-wave circuits seldom used in phase-sensitive detector circuits in servo systems?

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